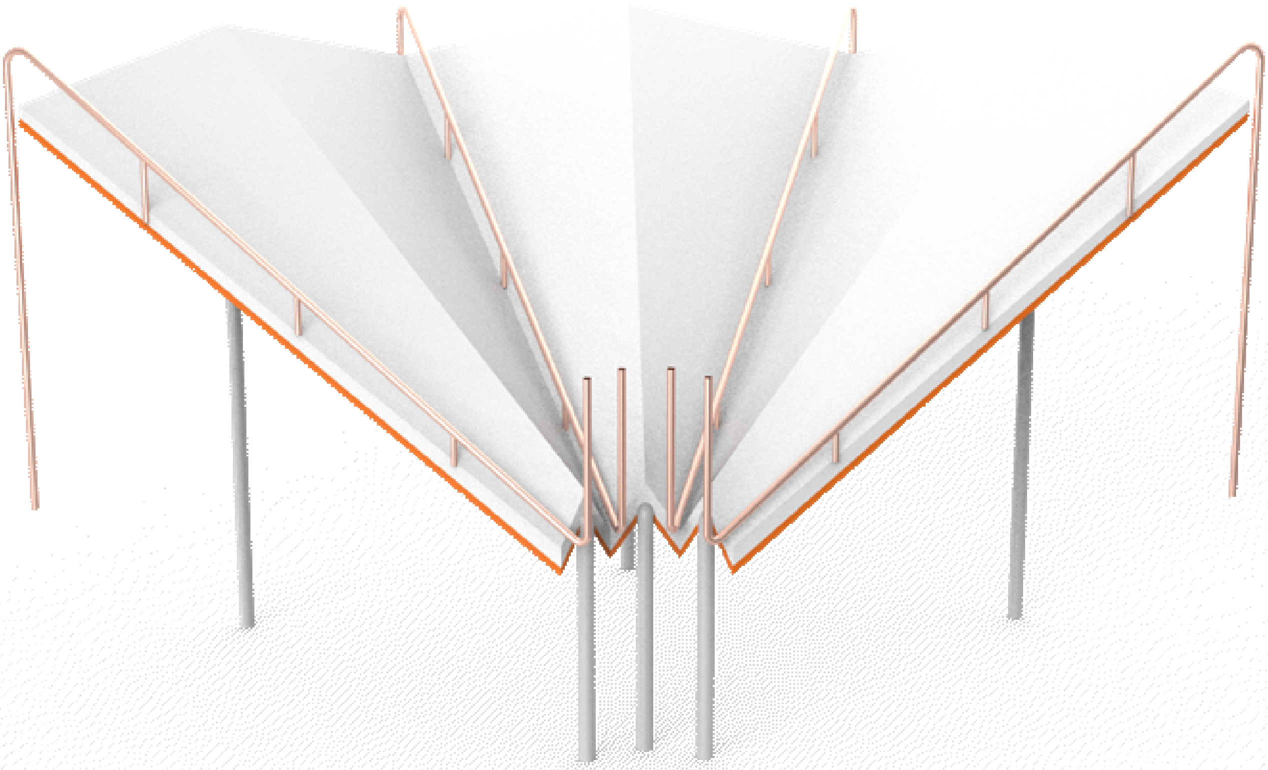
Reviewing and designing an Atmospheric Water Generator.



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Reviewing and designing an Atmospheric Water Generator.

Reviewing, comparing and designing an improved version of atmospheric water collector for rehabilitating the dry land and ecosystem affected by water scarcity.

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Abstract.

In recent decades, as a result of climate change and mismanagement, water scarcity and drought has become more frequent, affecting both the humans and the biodiversity drastically. As a result of such phenomena, more research has been done to find an alternative sustainable way of obtaining fresh water for afforestation and drinking water for human and animal consumption (Klemm et al., 2012), one example of such systems is Atmospheric Water Generator or AWG.

This study aims to design and improve AWG. The collector will be used for rehabilitating the dry land and affected ecosystem due to water scarcity.
To reach this aim, a literature review and comparison between existing methods of generating water from the atmosphere (i.e. active and passive) has been made in addition to studying other sources of inspiration such as plants and insects that collect water from the atmosphere.

The comparison between the collectors was based on the systems advantages and disadvantages, including their total water yield and final water cost per litre. The results showed that the active systems have the highest yield, but their high system complexity and need for external energy source (i.e. electricity) acts as obstacles when they need to be deployed to a remote area where locals do the maintenance and monitoring.

In passive collectors (i.e. fog and dew collectors), the dew collectors have the lowest yield compared to the fog collectors. Still, they have the most economical installation and maintenance cost in addition to having a straightforward and easy to maintain system. By improving the Dew condenser design, the total yield of the system will be improved, and the final water cost will be further reduced.

Based on the comparison results and nature inspiration (plants and insects), different versions of dew collectors were made and tested in a chamber. The results showed that the funnel-shaped condenser (cone angle of 60°) with additional edges at the bottom is the most efficient way of collecting and condensing water from moist air.

Further study and testing are required to fully evaluate the improved dew collector since the tested model in the dew chamber were scaled, and factors such as Infrared emissivity and ground heat flux were not considered. The future test should include 1:1 full-scale model of the collector in a site that meets the dew condensation parameters.

Keywords. Atmospheric Water Generator, Active water collector, Passive water collector, Dew collector design.

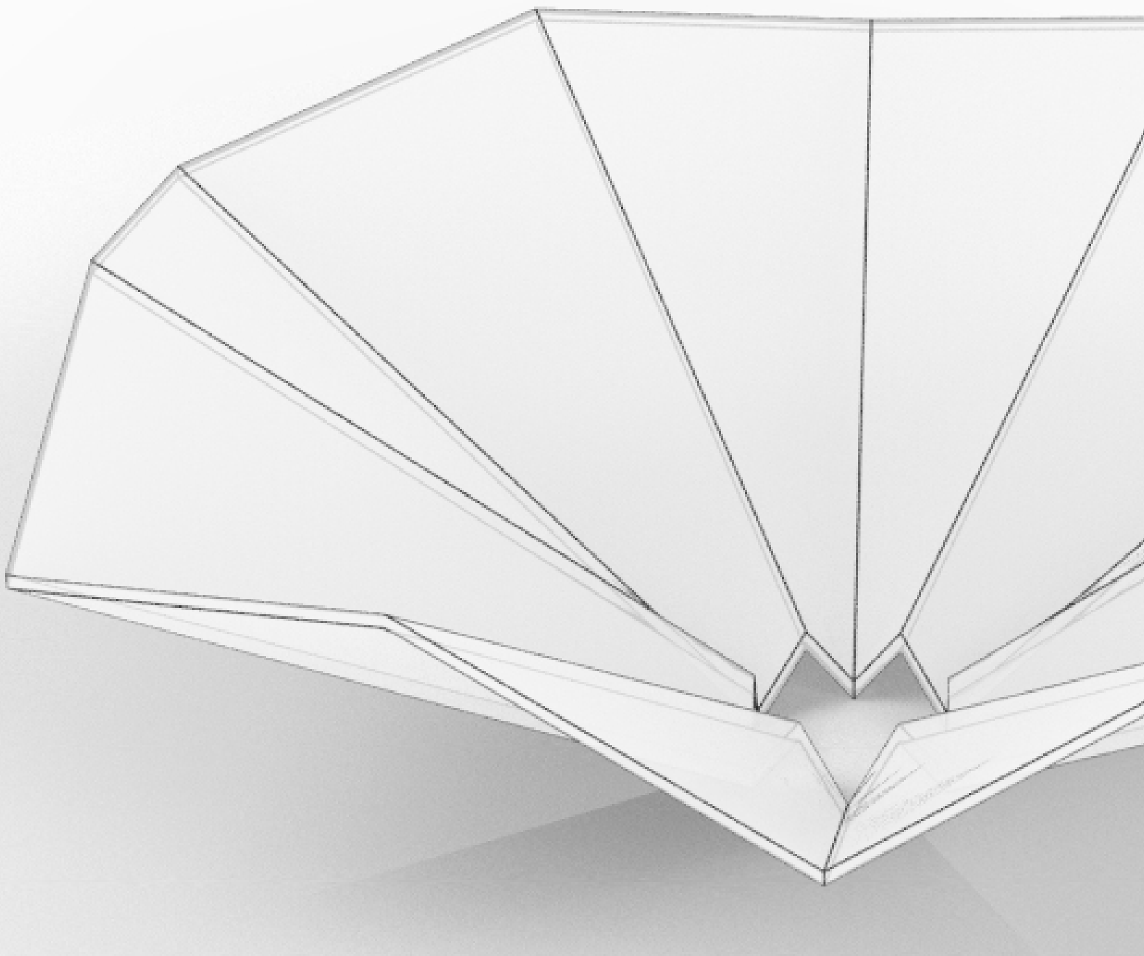
Contents.

Abbreviation

AWG	Atmospheric Water Generator
AWVP	Atmospheric Water Vapour Processing
IR	Infrared Radiation
LFC	Large Fog Collector
PE	Polypropylene
PETB	Polyethene embedded with microspheres of TiO2 and BaSO4
SEM	Scanning electron microscope
SFC	Standard Fog Collector
WHO	World Health Organization

01. Introduction

In following sections an introduction and background information regarding the Atmospheric Water Generator is given along with research aim, questions and methodology used in this thesis.



1.1 Background.

Collecting water from the air is nothing new; water from the air has been and still is extracted in nature daily. Example of this can be found in driest habitats of the world Namib Desert, e.g. in the south-west of Africa that is a habitat of Darkling beetles in which some of them collect the water from the dew and ocean fog on the sandy hills. They either use their body or built a small structure to collect the water or plants such as cactus that has an efficient water collecting system in place, with well-distributed spines and trichomes on their stem they collect fog water and even manage to defy gravity when the spine catches the water droplet at their tips (Ju et al., 2018).

Us humans also took note of such systems and invented our own structures (at first not as complicated as nature), until recently we had no idea that a beetle or cactus in arid areas are collecting water with the help of nano and macro structures on their elytra or spikes. But we made a primitive version of those systems in our way, for example the Zibold in 1912 built an aerial wells with dimensions of 20 meters wide, 6 meters tall and a diameter of 8 meters for upper portion, this was built on top of the mount in Feodosia (Beysens et al., 2006). Although the purpose of this structure was to condense dew water at the end the further research showed that it was collecting fog water, despite the initial aim, the structure produced 360 litres of water (Milimouk et al., 1995) every day for three years until the experiment was terminated due to failure at the base of the structure.

In recent decades, as a result of climate change and miss management, water scarcity and drought are becoming more frequent, affecting both the humans and the biodiversity drastically. As a result of such phenomena, more research has been done with the aim of finding the alternative sustainable way of obtaining fresh water for afforestation and drinking water for human and animal consumption (Klemm et al., 2012), one of such systems is Atmospheric Water Generator or AWG.

Atmospheric Water Generator (AWG) is a system extracting the water from humid air. In nature, this happens as fog or dew (Nikolayev et al., 1996). For collecting the water from moist air, there are currently two methods available:

1. Passive AWG systems such as fog water harvesting system with the use of nets and supporting structure (Schemenauer and Cereceda, 1994) or dew collection system using plastic foils or other types of sheets to condense water without the use of external energy source (Clus et al., 2008).

2. Active AWG systems, in which the condensation process is stimulated artificially with an input of external energy source such as electricity to condense the water by using components, such as cooling compressor, heat exchanger, humidity condenser, fan and water tank to cool down the air and collect the water in the process (Emec, Bilge and Seliger, 2015).

Each of these systems has its benefits and disadvantages. Passive AWG uses modern materials in long-lasting, simple devices (i.e. such system can run using a synthetic net, poles and water tank) that can be maintained with minimum external expertise (Wahlgren, 2001). However, its disadvantage is the low water production and its sensitivity to wind, temperature and humidity level (Clus et al., 2008). As for active AWG, they require high initial investments and additional power source, but they are very effective and efficient in terms of producing a larger volume of drinkable water compared to passive AWG systems.

AWG has been used in different projects, for instance in a farming project in Cyprus using active AWG (Emec et al., 2015), dew water collecting system in Pacific islands of French Polynesia (Clus et al., 2008) or fog water collections system in Chile and Peru (Schemenauer and Cereceda, 1994). The outcomes of projects show that the amount of water produced by different AWG systems dictate their usage and the place they can be used. For example, most of the passive AWGs are perceived as complementary water sources in drought season (Berkowicz et al., 2004).

Moreover, they are very location-specific. For instance, the fog water collection system can only be deployed in particular locations like mountainous and coastal areas (Nikolayev et al., 1996). On the other hand, active AWGs are less location-specific and can recover dew water in larger volume and become the primary source of water.

The AWGs are dependent on environmental factors, such as temperature, altitude, humidity and wind. Selecting the right site for testing or using the specific type of AWG is crucial. Depending on the type of the generator, the particular factor might be bolder than other during this research factors that are important for each generator is studied and categorized accordingly. After reviewing the AWG types and their working variables, a kind of generator with the most room to improve is selected, followed by designing and testing the concepts in a chamber made for water condensation.

1.2 Aim and research questions

This thesis is aiming to address the following research question:

- Which one of the AWG methods have the most room to improve?
  The following question is addressed by reviewing current methods of producing water from moist air (i.e. AWG) and finding the variables that affect their water production.

- In what way the selected AWG method can be improved to yield more water?
  The improvement is done by studying the existing examples and taking notes of nature and biomimicry.

The objective is to find the optimum system to generate water from air for specific use and location that fits the criteria of the selected method. This objective includes locals involvements and availability of the system materials and parts in the particular country or destination of the AWG testing site. The water collected from the system will be used to rehabilitating the dry land and affected the ecosystem due to the water scarcity, and the effect will be documented.

1.3 Methodology

According to the aim of the study, the nature of the thesis is experimental research which includes two following phases:

- Research and development phase
- Designing, concepting and testing

In the first phase, existing studies on the topic are collected and analysed (benchmarking the existing methods) for developing an AWG system. Document analysis includes both a qualitative literature review and quantitative data analysis to establish an AWG system with the most room to improve.
In the second phase, after selecting the type that can be improved, the designing and concepting of new collector are done. After the concepting, the scaled model of the concepts is built and tested in the chamber to study their potential in harvesting water from moist air.

02. AWG

In following sections different types of Atmospheric Water Generators as wells as examples in nature are studied in details. At the end of the section a comparison between different methods is made with an aim of selecting one AWG method for further improvement.

2. AWG

Collecting water from the air depends on the amount of water vapour in the air, availability or density of water vapour depends on factors such as locations, for example, a location next to a large body of water such as sea have more water vapour in the air than a desert, temperature is also a factor since higher temperatures can hold more water vapour than cold air.

Other factors such as pressure/altitude and time of the day (since it directly relates to the temperature) also play essential roles in the amount of absolute humidity.

From the above points, it can be concluded that in general, the AWG will have a better yield at locations with high average temperature, high absolute humidity and positions close to earth surface since there is higher water vapour density.

Potting or collecting water from moist air requires energy unless the phase change happens naturally through the course of temperature or pressure change, i.e. dew formation at night on the grass, on cactus spines or on the back of Beatles from the morning fog or fog formation due to change elevation and temperature.

To form water from moist air, first, the hot, humid air needs to be cooled down to well below the dew point, since cooling down the air will decrease the kinetic energy of the water vapour molecules and increase the probability of the bonding and forming liquid water droplets (Wahlgren, 2001). When the phase change (water vapour to water droplet) is happening energy in the form of heat is released; it is crucial to dissipate the latent heat to preserve the formed water vapours otherwise they will evaporate.

Latent heat or energy released from the condensation process of 1 ml water at 20 °C is 2500 J the amount of energy required to boil water and break the H2O bond is the same amount for transforming the moist air/gas to liquid. This amount of energy is equal to 1 min use of 40W lamp (40 J in 1s and 2400 J 1in 1 min).

2.1 AWG types

With drought and water scarcity becoming more drastic throughout the world due to climate change, more attempts are made to collect fresh water from alternative sources. One source of water that has been proven to be reliable and available in arid to semi-arid areas is water vapour available in the hot, humid air.

Although such devices are not new concepts (oldest atmospheric water generator is Zibold condenser or aerial well made around 1951 by Fridrich Zibold) (Beysens et al., 2006) there are currently many different types of water vapour condensers available on the market. Following sections are summarizing the presently available technologies and methods of condensing water vapours and further research and comparison are done by looking for alternative water vapour harvesting methods in nature, i.e. plants and insects.

2.1.1 Active AWG: Surface cooling - Heat pumps

Heat pump and Atmospheric water vapour generator

Here the principle of the device is similar to a fridge or an air conditioner, using a compressor to pressurise and increase the temperature of the particular type of refrigerant. The refrigerant is the main element of the system due to their lower boiling temperature; the system can be efficient in absorbing and extracting heat rapidly. Examples of the refrigerants are CFCs or Chlorofluorocarbons, HCFCs or Hydrochlorofluorocarbons and HFCs or Hydrofluorocarbons.

After the refrigerant is compressed and pressurised in the compressor, the heated gas will go through a coil/condenser to get the heat out and cool down the gas into liquid form while maintaining the high-pressure state. The liquid refrigerant will run through a Thermal Expansion Valve or Capillary tube which results in sudden drops of pressure and temperature of the liquid coolant resulting in liquid/vapour mix form, the cooled liquid will take the heat from its warmer surroundings while going through the evaporator during which it will vaporise and will be forced back to the compressor where the process repeats itself (Fig. 01).

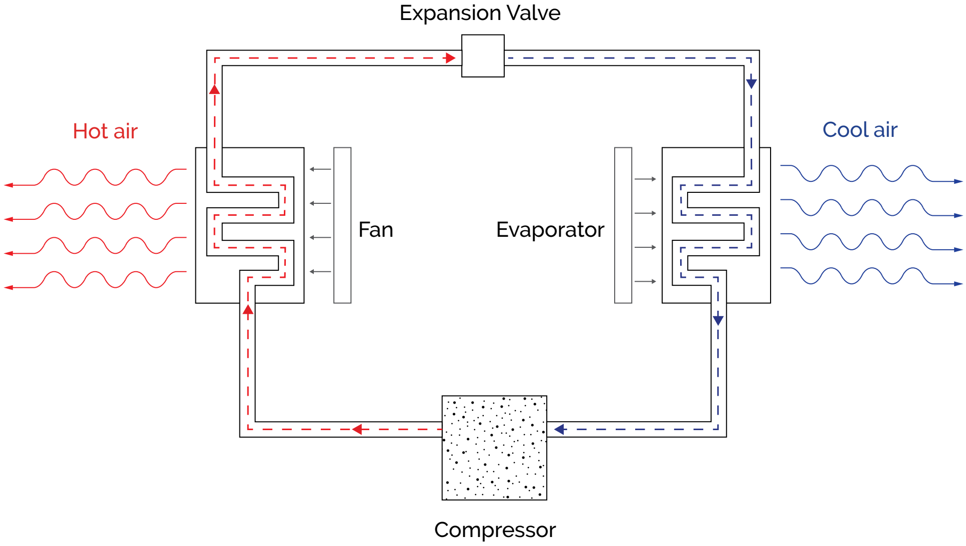


Fig. 01. Illustration of a refrigerator or air conditioning systems

In Atmospheric water vapour processing (AWVP) system, such a process is referred to as surface cooling processes. The core principle is the same as the process explained above, with the main aim of collecting the condensed water vapours from the process. In Fig 2., a heat pump - water vapour processor is summarised.

In the heat pump or active water vapour systems, the moist air is sucked in through an air filtration system and passed through the evaporator (using a cooled pressurised refrigerant gas) with the aim of dropping the air temperature to 6-7 °C (Harriman 1990). The resulting condensed water vapours, formed on the cooled surface/heat exchange surface are then collected in a tank, and further filtration is done to achieve drinkable water.

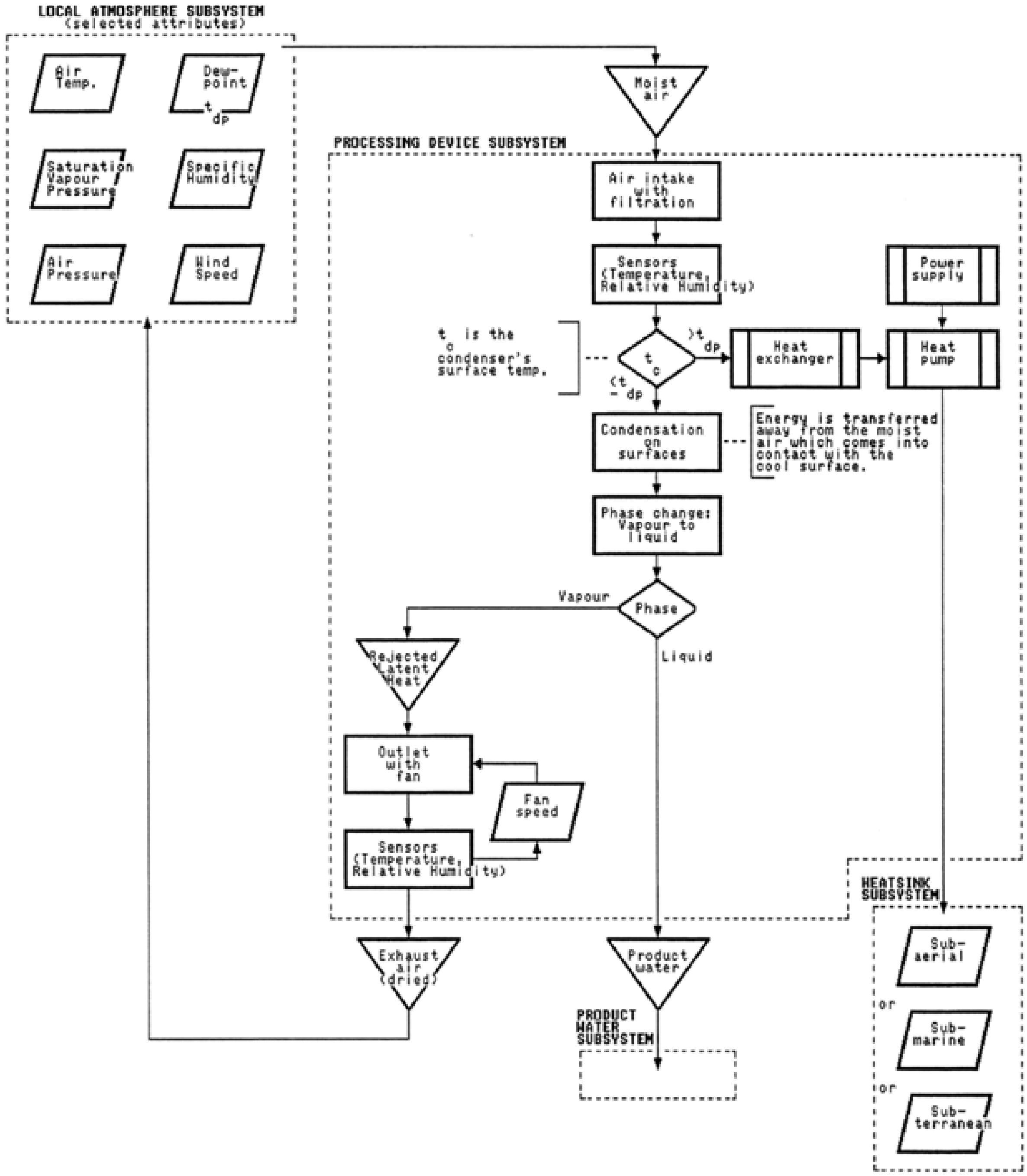


Fig. 02. Explaining how water condensation happens (Harriman 1990)

Most commonly used refrigerant is Chlorodifluoromethane (CFCs) which is linked to ozone depletion. To minimise the usage of the harmful gas some projects such as Electronic household plant watering device (Peeters et al., 1997) used a thermoelectric heat pump or Peltier (an electrically driven device that transfers the heat from one side of the device to the other) as a heat pump to move the heat away from the moist air and condense water on a surface.

Other methods for condensing water vapours on the surface using a heat pump involves usage of a subaerial heat sink for transferring the heat from the cooled surface into ambient air, a submarine heat sink using deep ocean cold water for transporting the sensible heat away from the moist air and use of underground heat sink.

Advantages and disadvantages of the heat pump systems are listed in table 1.

Advantages	Disadvantages
• Well developed technology (Harriman 1990) • Availability of the components • Maintenance expertise fairly common (Wahlgren 2001)	• Harmful components such as Chlorodifluoromethane (CFCs) might be present in the system • High power consumption • Difficult to achieve even cooling of the incoming moist air (Wahlgren 2001) • Difficult to achieve dew point below 4.5 °C • Frost may reduce the performance and cooling process • High power requirement • Air filtration needs regular replacement

Table 01. Advantages and disadvantages of Heat pump and AWV systems.

2.1.2 Passive AWG: Radiative cooling and Fog collectors

Radiative cooling

Here the principle of the device is similar to a fridge or an air conditioner, using a compressor to pressurise and increase the temperature of the particular type of refrigerant. The refrigerant is the main element of the system due to their lower boiling temperature; the system can be efficient in absorbing and extracting heat rapidly. Examples of the refrigerants are CFCs or Chlorofluorocarbons, HCFCs or Hydrochlorofluorocarbons and HFCs or Hydrofluorocarbons.

After the refrigerant is compressed and pressurised in the compressor, the heated gas will go through a coil/condenser to get the heat out and cool down the gas into liquid form while maintaining the high-pressure state. The liquid refrigerant will run through a Thermal Expansion Valve or Capillary tube which results in sudden drops of pressure and temperature of the liquid coolant resulting in liquid/vapour mix form, the cooled liquid will take the heat from its warmer surroundings while going through the evaporator during which it will vaporise and will be forced back to the compressor where the process repeats itself (Fig. 01).

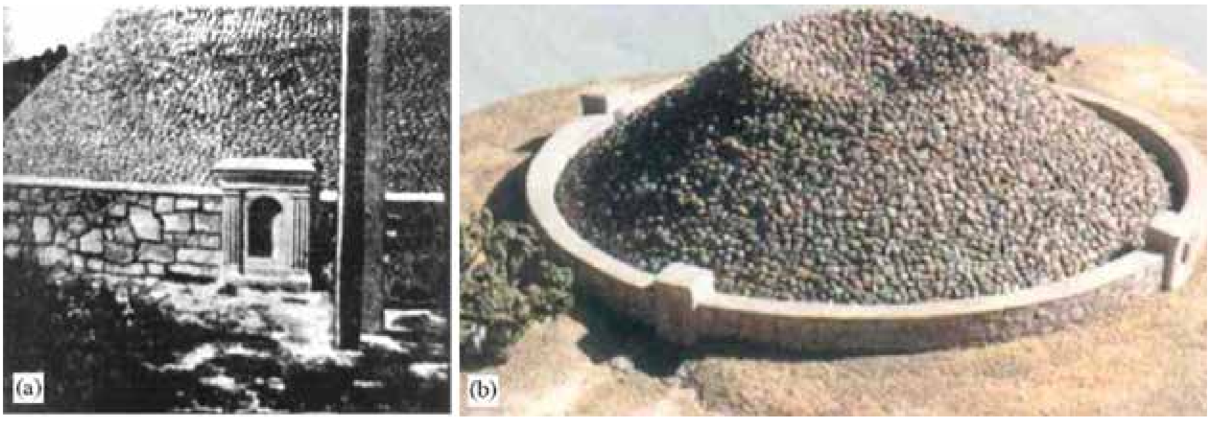


Image. 01. (a) Photo Zibold condenser in 1912. (b) Zibold condenser model in 1912 (photo D. Beysens). (Beysens et al., 2006)

Zibold's condenser produced 360l (Milimouk et al., 1995) every day for three years until the experiment was terminated due to failure at the base of the structure, although this seemed a successful project other similar projects couldn't replicate the results. Now the researchers (Nikolayev et al., 1996 cited in Beysens et al., 2006) believes such structure could not work for dew condensation, due to the fact that the surface temperature of the stones in such a large structure could not possibly reach the dew point hence the condensation will never happen, in other words, lower mass will perform better since it can radiate heat in much faster paced. They also speculate that the water that was gathered in Zibold condenser might have been the result of fog interception.

Current dew condensers condense water vapour on a surface when the condenser surface temperature drops below the dew point temperature of the surrounding air, this happens due to radiation exchange between the surface and atmosphere (Beysens, 2003).

This makes the material used for condensation extremely important since it has to cool down the surface below the dew point to achieve the water formation but due to the limitation of cooling power of such materials and energy required (2450 J/g at 20 °C for 1ml of water) to condense water, dew yield of such systems are generally falling down to 0.51 l/m2 to 0.8 l/m2 (Monteith, J. L. (1957), although 0.8 l/m2 is theoretically the maximum possible yield. Still, this amount is yet to be reported from existing dew collectors, and the highest recorded yield is 0,6 l/m2 per night from the dew collector in Jerusalem that being said, such systems are still viable and can produce a large quantity of water when assembled in large areas or on rooftops.

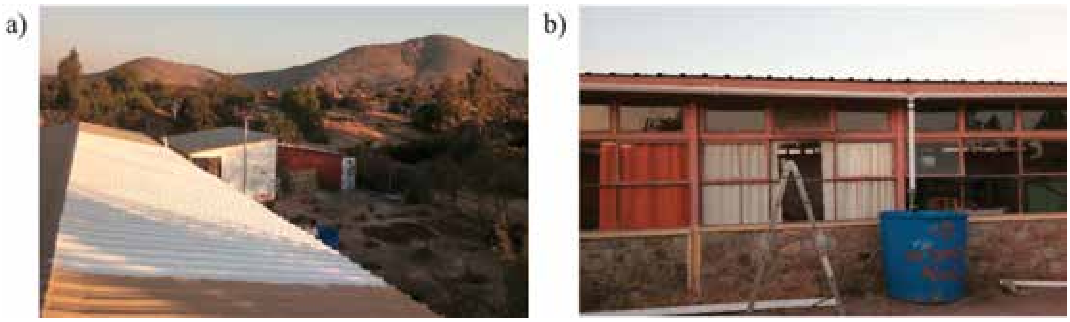


Image. 02. (a) Photo of the southern side of the Zibold condenser in 1912. (b) Model of the Zibold condenser in 1912 (photo D. Beysens). (Beysens et al., 2006)

Passive dew condensation process correlates directly to the following parameters:

1. Atmospheric parameters,
2. Geometry of the dew collector
3. Material properties of the condenser surface. (Beysens, 2013).

1. Atmospheric parameters

Atmospheric parameters include air temperature, dew point temperature, relative humidity, cloud coverage and wind speed (Lekouch et al., 2011).

Since the system relies on passive radiation and natural thermal convection, the wind has significant effects on the system. Wind speed larger than 4.4 m/s will stop the condensation process since the heat exchange between the foil and atmospheric air happens too fast and prevents the water vapour phase change. Idle air is also not favourable since the moist air around the system needs to be refilled continuously at a rate that doesn't interfere with the thermal exchange process; according to Beysens ideal wind speed for such system is 1 m/s, but the working range would be lower than 4-5 m/s (Beysens, 2013).

Shape and materials of the system are also essential, even though the atmospheric factors remain the same different dew collector with different materials and shapes/geometry will yield different results, a variation of 40-400% of improvement can be found (Clus et al., 2009, Beysens et al., 2013) in the systems that take into account an optimum shape for collecting the dew and efficient drop collection system with the use of the best material for the foil surface.

2. Geometry

Most commonly used condenser shapes are:

i. Planar condensers (e.g. foil plane tilted at 30°)
ii. Hollow condensers (e.g. cones or funnel and pyramid shapes)
iii. Mixed (e.g origami shape).

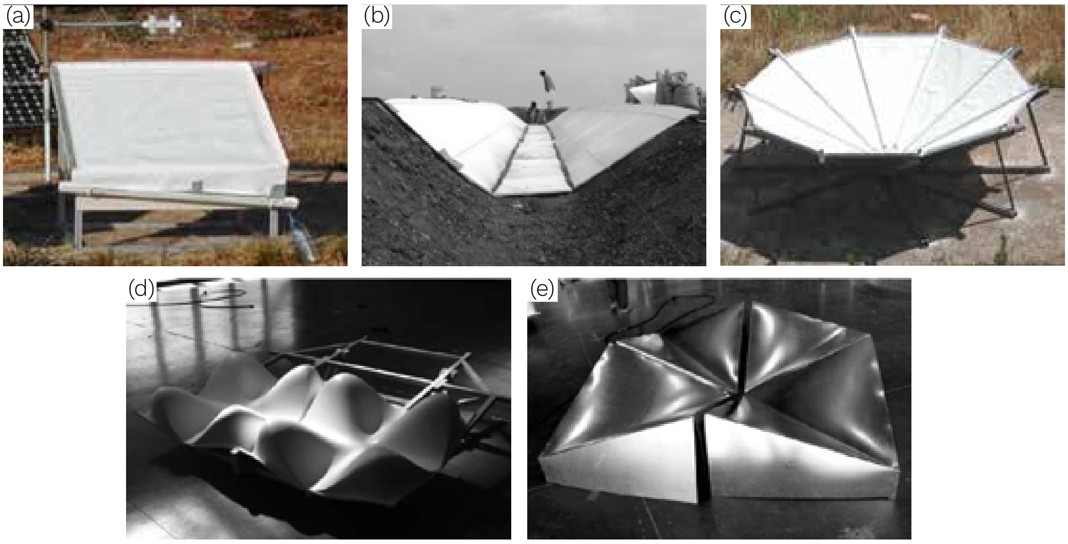


Image. 03. (a) Planer condenser. (Beysens, 2013) (b) in ground condenser (Sharan et al., 2011) (c) Funnel-shape condenser (Clus et al., 2009) (d) Origami condenser (Beysens, 2013) (e) Origami condenser (Beysens, 2013)

To study, compare and improve different shapes of condensers, researches are using Computational Fluid Dynamics (CFD), although building one system seems easy, testing and analyzing the systems are lengthy process (at least a year of monitoring), but with CFD, one can implement and calculate the heat exchange between the foil and atmospheric air and also include other variables such as wind, scale and of course test different geometries in a much faster manner.

i. Planar condensers are typically inclined surface with the condensing foil on top, the best angle for such system is 30°, but a horizontal arrangement is also very common to find among such systems.

   Since the foil is exposed, the wind direction and speed has significant effects on the overall performance of the system. Due to this, such systems are oriented to expose their insulated backs to the dominant wind.

   Below in Image 04. are some examples of such systems, the optimum result can be achieved when the planar condensers are positioned 1 m above the ground (Beysens et al., 2003) although other system placements are not uncommon such as the three trapezoidal ridges in the ground in Gujarat state at the north-west of India.

Image. 04. (a) 30° tilted condenser (b) Dew water collector for potable water in Ajaccio (Corsica Island, France) (c) Dew and rainwater collecting system in the Gujarat state of India (Sharan et al., 2011)

ii. Funnel condensers (a type of hollow shape condensers): an example of funnel shape condensers are presented in Image 05., In Clus research (Image 05 a) numerical calculations were made to compare the condensation capacity of conical to planar shape condenser. The result was 15-30% larger yields compared to planner condensers (Beysens et al., 2013).

Image. 05. (a) Funnel shape condenser with 7.32 m2 surface area with 60° cone angle(Clus et al., 2009) (b) inverted pyramid collector with an inclined surface of 30° (Jacobs, Heusinkveld and Berkowicz, 2008)

The performance improvement is due to the funnel shape reduces the heat exchange between the foil and air flow/wind(Clus et al., 2009) while it also holds the heavier cold air at the bottom of the cone due to buoyancy (Beysens et al., 2013). Due to its symmetrical shape, it can also block the wind from any direction and reduces the forced convection process.

To find the optimum cone angle numerical calculations were done between different angles (Fig 03) and the optimum angle of 30° (cone angle 60°) were found, which is also the optimal angle for plane condensers (Clus et al., 2009).

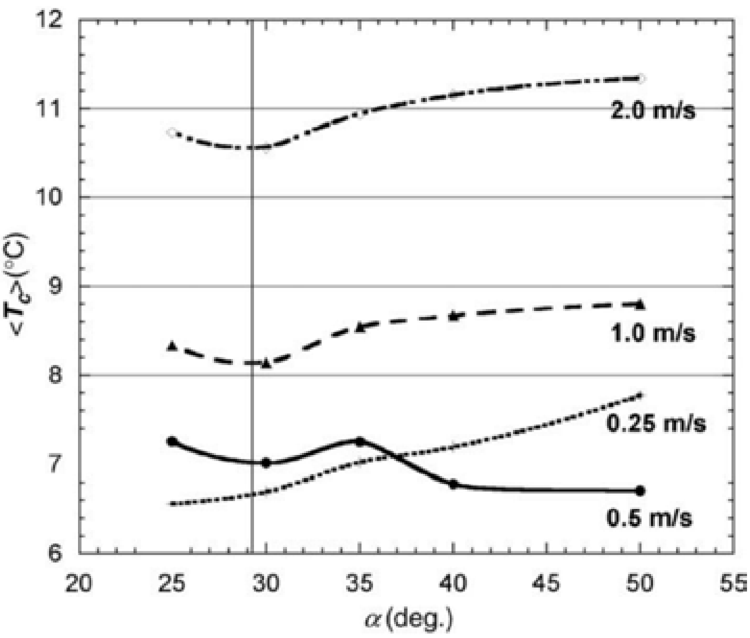


Fig. 03. Funnel mean surface temperature (Tc) with respect to the angle at various speed (Clus et al., 2009)

iii. Origami and egg shape (other types of hollow shapes condensers): The 3rd and most efficient shape of passive dew condenser is a mixed shape of hollow structure, an example of such shape can be found in Image 06.

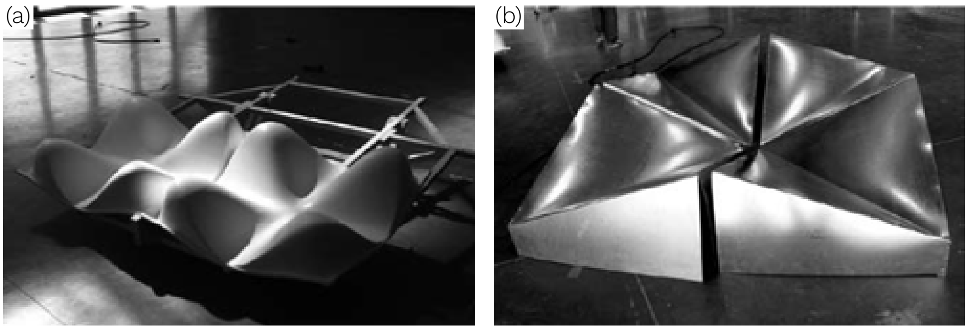


Image. 06. Fig 7. (a) Egg-box shape 2 m x 2 m (b) Origami shape (Beysens et al., 2013)

Egg and origami shaped condensers are results of research done by Beyssens aiming to improve the aesthetic, performance so that it can be used repeatedly on planar surface or curved surfaces i.e. rooftops. The prototypes were made and tested in Bordeaux urban area in France.

Unlike the rest of the condensers, origami and egg-box shape are not using OPUR foil, instead they are coated with a paint that makes the surface hydrophilic and provides high infrared emissivity (Beysens et al., 2013); they are also insulated with styrofoam.

At the test site, two condensers were tested against 1 m2 planar condensers using OPUR foil ("International Organization For Dew Utilization", 2019) set at an angle of 30° with a 20 mm polystyrene foam at the back for insulation. After 51 days of data collection the data showed a dew yield increase of 150% for egg-box shape and 400% for origami shape (Beysens et al., 2013) compared to planar condenser (comparison data is presented in Fig 04).

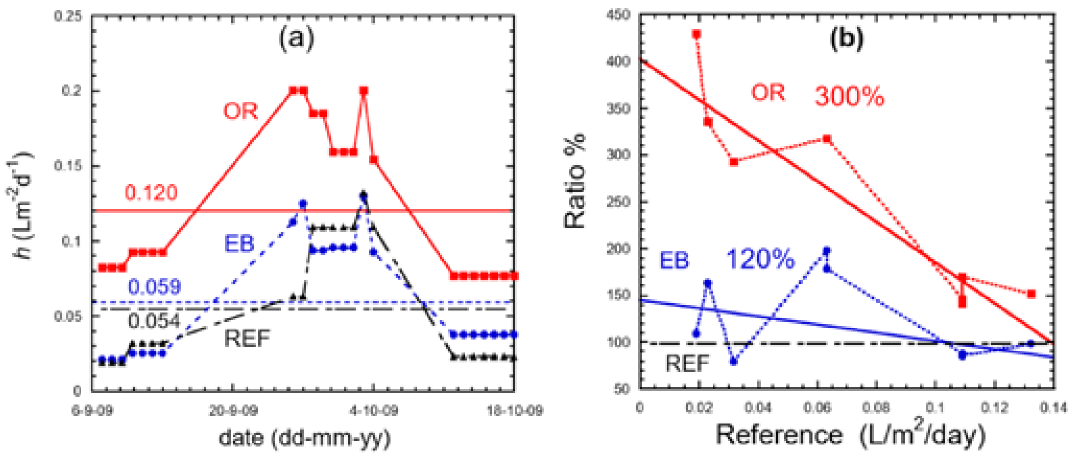


Fig. 04. Evaluation of dew yields for Origami, Egg box and Reference plane. (Beysens et al., 2013)

Hollow shaped condensers generally perform better than planar condensers, since they prevent the wind influence and reduce the heat exchange between the condenser surface and warmer air flow. The difference of performance between egg-box and origami is due to the shape differences, mainly the round bumps placed at the top of each peak in egg-box. Rounded bumps on top of the egg-box prevents the water flow since the angle is not optimum or enough for gravity to pull the water drops down to the base of the structure.

Other important factor that increased the dew yields of origami shape is the edge effect, Fig 05. is showing the positive effect that edge has on collecting the dew water.

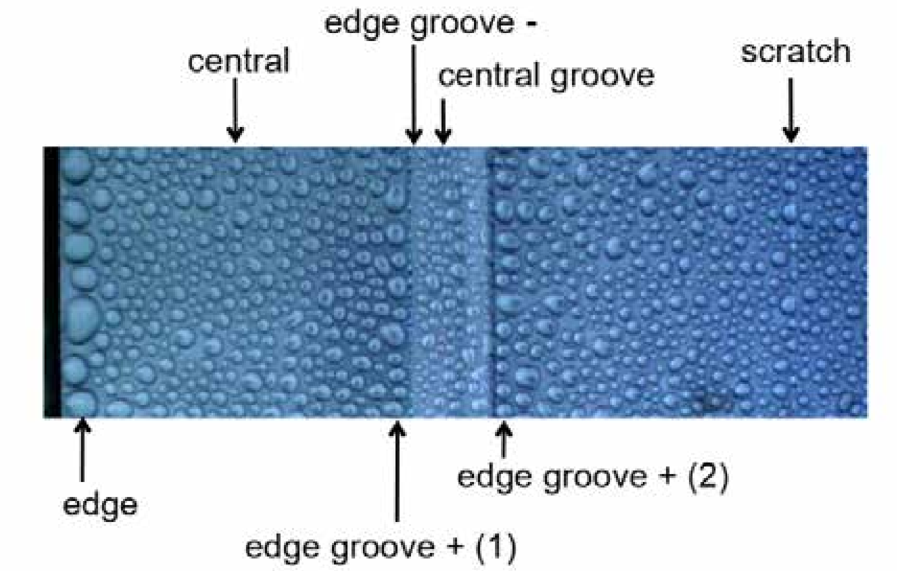


Fig. 05. Condensation on different part of the surface (Medici et al., 2014)

Dew formation and drops growth are more evident on the edges and corners rather than the middle of the surface, this effect can increase the growth by nearly 500% on edges or corners (Medici et al., 2014).

This effect happens due to the fact that the droplets on the outer edge has better access to the vapours in the air, compared to the droplets in the middle of the surface, where they have to compete with their neighbouring droplets to get to more vapours from the air. Due to this effect, the droplets at the outer edge grow faster and when they reach a critical size they will form a small stream where it collects other droplets in its way.

3. Material

Condenser materials that are used in such systems are PMMA/plexiglass, Polyethylene embedded with microspheres of TiO_2 and $BaSO_4$ (PETB) (Nilsson et al., 1994) other materials include Teflon, anti-UV PVC and white corrugated anti UV PVC sheets used on roofs. According to the International Organization for Dew Utilization ("International Organization For Dew Utilization", 2019), the best material for dew condensation is "polyethylene (PE foil with 5% volume of TiO_2 and 2% volume of $BaSO_4$" (Masetre-Valero et al., 2012)

Water quality

Depending on the location and the condition of the system the collected water might have different levels of contaminants since the foil is sitting in the open and collecting the water from its surface many harmless bacteria are also collected from the air into the water container, with that said the water collected in the container is not prone to contamination and it should be treated and disinfected before being used as drinking water. (Beysens et al., 2006),

Section Summary:
In summary dew collection in radiative systems can be improved by:

I. using the material with high IR emissivity (such as OPUR foil) or coat the surface with a paint that make it hydrophilic and provides high infrared emissivity.
II. reducing the wind effect on the system, since having too much wind (higher than 4-5 m/s) will cool down the surface much quicker and prevent the water formation on the condenser surface
III. avoiding and protecting the system from the ground heat flux (Beysens et al., 2006), this can be achieved by insulating the back side/the side facing the ground by using insulating polystyrene, Styrofoam or rockwool with the addition of aluminium foil,
IV. increase the dew condensation time
V. enhance dew drop recovery, according to the study done by Beysens the optimum angle for collecting dew with gravity is 30° surface (Beysens et al., 2003). Also having sharp edges and corners will increase the drops growth and improve the overall dew yield of the system.

Advantages	Disadvantages
• Low-tech • Affordable • Passive - no need for an external energy source • Portable • Can be used on rooftops to condense and collect dew water • Also, collect rainwater	• Limited yield of maximum 0.61 l /m2 per night • Larger areas or plants are needed to yield a higher amount of water • Low water quality • Further treatment and filtration is needed to make the water drinkable

Variables
- Air temperature
- Relative humidity
- Dew point temperature
- Wind speed (1-3 m/s is favourable for replenishing the air around the condenser surface)
- Cloud coverage - Dew generally forms under stable clear skies
- Sky radiation (Beysens 1995 cited in Beysens et al., 2006)
- Position (in relation to the wind and sun)
- Dew collector shape
- Condenser surface material

Fog Collector

Fog collectors are addressing the problem of providing fresh water in arid and semi-arid area for small or poor communities that don't have access to fresh water, it does this by implementing locally available materials in the design and lowering the overall cost of the project.

Fog collectors are low budget projects and site specific, meaning they are positioned where there is persistent fog. Ideally, such places are close to the ocean or sea where the hot moist air from the sea/ocean with help of dominant wind moves toward the land and due to natural land elevation (i.e. hills or mountains) along with pressure and temperature differences the moist air turn into fog (advection fog) and passes through the land.

Other important factors for fog collector beside the geological position is the maintenance factors of such structure. Due to cost saving factors of the project often the structure (either the net or the frame and in some cases both) are not strong enough to withstand the strong wind due to this often the fog harvesting net is torn apart or the structure collapse under the strong wind. Due to lack of expertise and economic resources between the locals, the whole project or specific structure is abandoned (de la Lastra., 2002).

Based on the research done by Fessehaye, majority of the collected water from the fog collectors are mainly used for domestic water supply while the rest is used for irrigation and research (Fig 06.) (Fessehaye et al., 2014).Fog water in irrigation sector has been used for reforestation or supplementary income for locals, for example the fisherman in Falda Verde, Chile used the water drip-irrigate Aloe Vera over the course of nine years (Carter et al., 2007 cited in Fessehaye et al., 2014) or Pinus pinaster and Quercus ilex trees seed were planted and drip-irrigated for two years in Valencia, Spain (Valiente et al., cited inFessehaye et al., 2014).

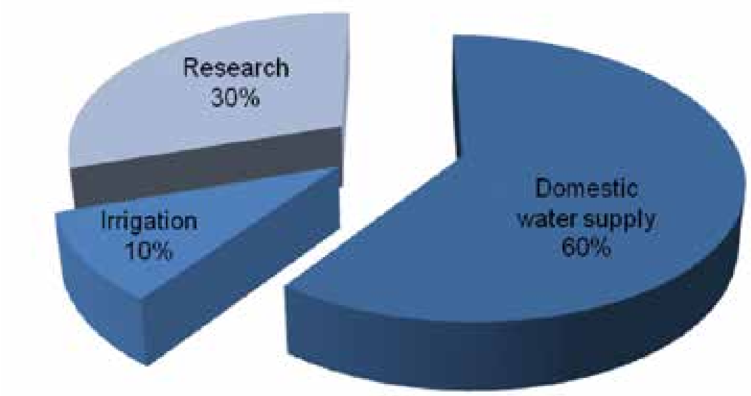


Fig. 06. Global fog water utilization (Fessehaye et al., 2014)

Fog collecting device rely on availability and intensity of the fog, there are different types of fog and each has different levels of liquid water contents. As a rule of thumb, "fogs produced by advection of clouds over higher terrain tend to have higher liquid water contents than fog at the land or sea surface" (Batisha., 2015),Fog collecting process correlates directly to the following factors:

1. Geological position and factors (fog availability, global wind map and topography)
2. Shape of the collector
3. Mesh type of the net.

1. Geological position

The fog collectors positions are by far the most important factor. After the first study done by Carlos Espinosa in Chile, 1957 (Gischler, 1991 cited in Holmes et al., 2015), the potential of the fog collectors for providing the fresh water was noticed and since then numerous projects were launched in Africa, Asia, South and Central America (Batisha., 2015) Fig 10 is showcasing the successful projects in collecting the fog until 2012 (Klemm et al., 2012). (full list of the projects in table 2 and Fig 07).

	Country	Location	Remarks and comments
Continent: *South and Central America*			
1	Chile	Coquimbo region, El Tofo	The project provided fresh water for about 100 families by taps in their homes
2	Chile	Padre Hurtado	Providing water for visitors to a church sanctuary and for gardening between 1999 and 2004
3	Chile	Peñablanca	Used for afforestation with native trees and for environmental education
4	Chile	Falda Verde	Delivering water between 2001 and 2010 and now being operated as a demonstration project
5	Chile	Alto Patache	Used as a platform for ecosystem and climate research. With average fog collection rates of about 6 L m^{-2} day^{-1}
6	Peru	From Trujillo in the northern to Tacna in the South	Many projects have been developed by the communities Provide water for afforestation and restoration of the degraded coastal ecosystems Used to grow fruits and provide fresh water for the population
7	Ecuador	Pachamama Grande	Very large collection efficiencies of up to 12 L m^{-2} day^{-1} were identified for high mountain regions
8	Guatemalan	The village of Tojquia in the Western Highlands at 3300 m above MSL	There are 35 LFCs producing an average of 6300 *l* of water per day during the 4–6 months in winter dry season. In the wet season, the water yield is even larger due to the collection of rain water as well as fog water All the LFCs built since 2006 are fully operational Strong community involvement
9	Dominican Republic	Islands in the Caribbean	The fog collection rates show that large-scale projects could be successful
10	Haiti	Islands in the Caribbean	The fog collection rates show that large-scale projects could be successful
Continent: *Africa*			
11	South Africa	Soutpansberg Mountains, Eastern Cape, West Coast village	Water collection rates ranged from 1 to 5 L m^{-2} day^{-1} and exceeded 10 L m^{-2} day^{-1} in the mountainous regions at elevations higher than 1700 m above MSL Supplement domestic water supplies Provide drinking water at schools
12	Namibia	Namib Desert	The quantity and the quality of fog were sufficient to justify a fog collection project
13	Eritrea	The villages of Nefasit and Arborobo	To increase access to drinking water for schools and 120 families The collectors needed high maintenance and close supervision during high wind conditions The fog collectors now serve as a demonstration of the potential for fog collection for the whole of Eritrea
14	Tanzania	Mt. Kilimanjaro	A large evaluation project
15	Ethiopia	Debark	A large evaluation project
Continent: *Asia*			
16	Nepal	A pilgrim temple	A medium-sized fog collector with 20–30 m^2 mesh area is being developed and tested
17	India	Several parts	There is considerable interest in fog collection where some evaluations are beginning
18	Oman	Dhofar	In the upper elevations very high average collection rates of 30 L m^{-2} day^{-1} for the monsoon period The fog water is only available for 2 months/year
19	Yemen	Hajja, Sana'a	Average 4.5 L m^{-2} day^{-1} over 3-month dry winter period
20	Saudi Arabia	Asir region	Fog collection rates of about 2 L m^{-2} day^{-1}
Continent: *Europe*			
21	Croatia	Mount Velebit	The collection rates of up to 4 L m^{-2} day^{-1} can be achieved during the dry summer season
22	Spain	Iberian Peninsula, Mount Machos	Fog total values reaching 7 L m^{-2} day^{-1} Fog water was included as a supplementary water resource in a forest restoration The survival of the two planted species had improved with the use of irrigations with water from fog

Table 02. Fog harvesting projects around the world (Batisha, 2015)

Location of the device is an important factor since certain types of fogs are favourable over the rest; fog that are made due to high elevation (advection or orographic type) are the main source of water for such devices since they have a higher level of water content compared to the fog that are made on land or sea level. Due to this reason majority of the fog collectors are located along the ridges mountains where there are no terrain to obstacle upwind of the site. (Batisha., 2015).

Fig. 07. Successful fog collecting projects around the world (Klemm et al.,2012)

Availability and frequency along with the placement of the fog collector has a profound effect on the system yield. This can be demonstrated by presenting the collected data from fog collectors around the world; from an average of 6 L/m2 (from 14 years of data collection, Alto Patache fog oasis in the Atacama desert, Chile) (Calderon et al., 2010), 10 L/m2 (In Tenerife Islands) and 4.5 L/m2 (In north of Sana'a and inland from the Red Sea in Yemen) (Marzol et al., 2010).

Since the wind is the only force moving the fog, finding the right place in accordance to topography and global wind pattern is also crucial factor for fog collectors yields, neglecting this can drastically decrease the yield, e.g. identical fog collectors were placed in Boulaalam, Morocco 4km from the coast and in Boutmezguida 30km from the coast, collected data over the course of two years indicate 1.9 L m-2 per day for Boulaalam and 7 L m-2 per day for Boutmezguida fog collector (Batisha., 2015).

Beside the initial factors such as water scarcity and the need for alternative water source in the specific area, the exact location of the site is selected based on geological information such as altitude, distance from the sea, relief and slope orientation using cartographic analysis, geological information systems, remote sensing analysis and preliminary field assessment (Schemenauer et al., 2005 cited in Fessehaye et al., 2014). Such processes are necessary for the success of the project and it is worth mentioning that acquiring this information will add cost to the overall cost of the project.

2. <u>Structure and shape</u>

Standard shape (Fig 08) of the fog collector is a frame that supports the mesh in vertical plane. The mesh is installed on two supporting poles and further support is given by cables or guy wires around the structure. Water from the mesh is then collected at the end of the mesh in plastic pipe and transferred to a reservoir.

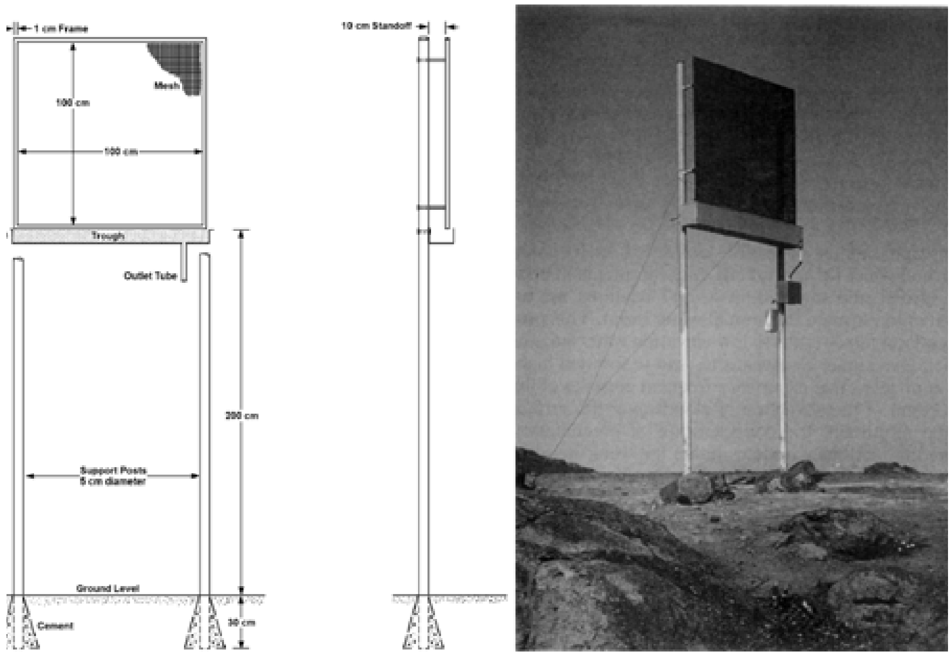


Fig. 08. Standard fog collector (Schemenauer & Cereceda, 1994)

Standard fog collector is installed and tested first in new test site before deploying large scale collectors, since the size and material is standard across the world the documented results can be compared to other test sites and therefore the potential of the site for harvesting fog water can be evaluated accordingly.

After the initial test, larger fog collector can be installed to maximize the water output. An example of large fog collector is presented in Image 07. this particular fog collector is 12 m by 6 m with 18 m2 flat panel Raschel foge collector mesh in Machos, Spain (Batisha., 2015).

image 07. Standard fog collector (Schemenauer & Cereceda, 1994)

Fog collectors are placed as high as possible from the ground to maximize the fog collection and fog interception, this height is typically 2 m. Vertical design of the fog collector is due to the fact that it should always face the dominant wind that brings the frequent fog, the only problem with such design is that the length and height of the collector is only adjusted for maximising the yield of the system without taking into consideration of exceptional high wind that can tear apart the mesh.

As mentioned before most common fog collector shape is flat mesh net panel supported by poles and wires, but in special cases where the wind speed is too high or there are more than one fog direction the shape of the panels become different.

In Image 8. three experimental fog collectors are presented, Eiffel, Harp and Diagonal Harp. These prototypes are part of a project in 2007-2008 tested in coastal hills on the outskirts of Lima, Peru. The aim was to maximize the efficiency of the fog collectors to improve other economical and ecological effect of such device in the test site . Out of three mentioned design the most efficient design was Eiffel, with ten times more water collection yield compared to Standard Fog Collector (Domen et al., 2011).

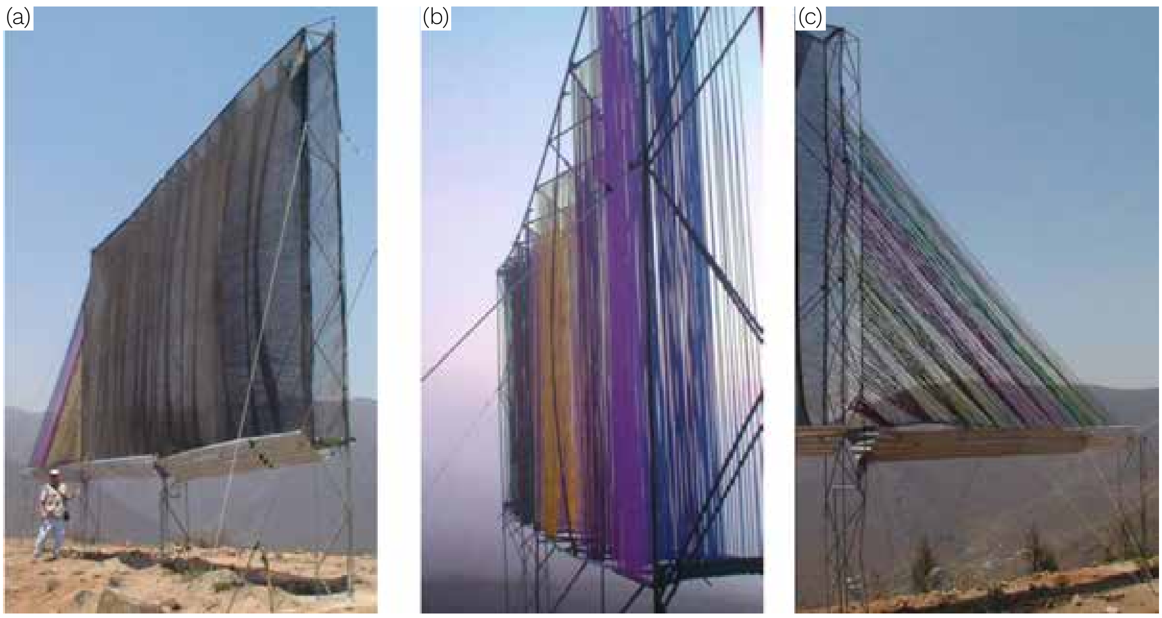


Image 08. Three experimental fog collectors, tested in Lima, Peru.
(a) Eiffel (b) Harp (c) Diagonal Harp (Domen et al., 2011)

Eiffel fog collector design improves the water harvesting process by increasing and filling the fog interception area, this is done by implementing three dimensional mesh. It consists of two flat mesh panels of 4x8m with 50% shade coefficient Rachel mesh and ten additional stripe of mesh between the two layers (Domen et al., 2011).

Although this design showed promising results in harvesting fog water, but it is still vulnerable to be damaged in high winds and extreme weather conditions, this is due to the fact that it increased and filled the area that intercept the wind and fog, resulting in more resistance/force on the structure and mesh in extreme and high wind speed situation.

In a more systematic approach using CFD, researchers studied the effect of wind pressure on fog collector and redesigned the structure accordingly. Since the only driving force of fog is wind, all the fog collectors are positioned in windy sites since more fog passing through the mesh will result in more water collection and this is only possible by having a higher wind speed.

Although wind is an important factor in fog collector yield, very little attention has been given to it in the design process. In general wind speed greater than 17 m/s will cause some level of destruction to existing collectors, in El Tofo-Chungungo project wind storms destroyed some large fog collectors every 2-5 years (Lastra et al., 2002 cited in Holmes et al., 2015).

Image 09 is presenting sets of examples of fog collectors in Pena Blanca, Chile and the effect of high wind pressure on the collectors.

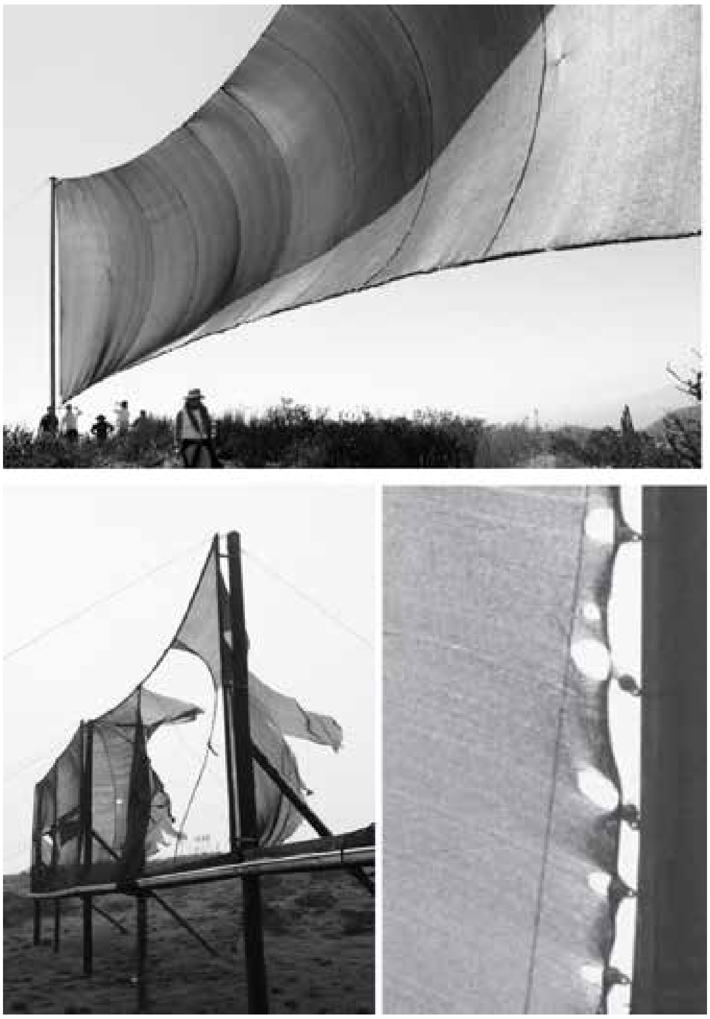


Image 09. Wind pressure may result in mesh rupture when the forces exceed the tensile resistance of the fibres. (Holmes et al., 2015)

Using CFD Holmes suggested multi funnel Large Fog Collector that can withstand high wind pressure while improving the average wind speed at the mesh surface which results in an increase of drag coefficient and provides flux continually. In addition, it increased the overall efficiency and yield of the system by 2.5 times more than flat panel collectors.

Funnels are modular panels that are placed in 60° angles facing each other towards the dominant or most frequent wind direction (Fig 09.), using 2 mm wide ribbon, double layer Raschel mesh with 35% shade coefficient or single layer mesh with 50% shade coefficient, with total structure size of 12 m by 9 m (Holmes et al., 2015).

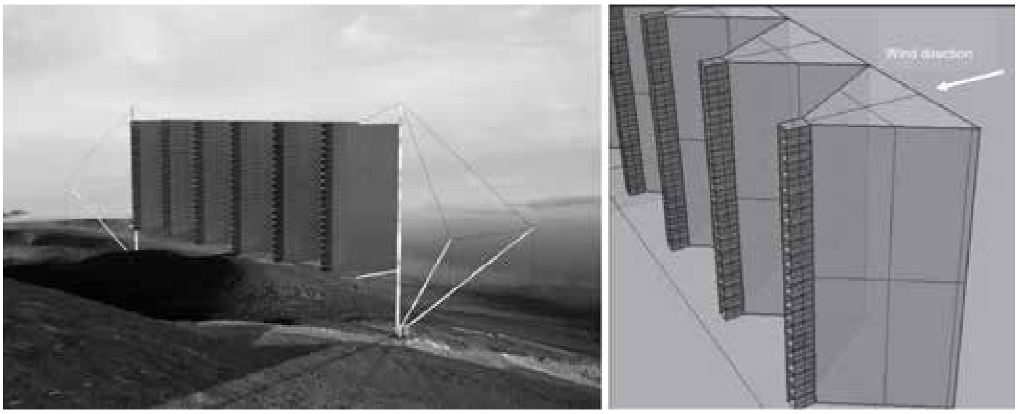


Fig 09. Multi-modular Funnel fog collector (Holmes et al., 2015)

In more recent years a company named Aqualonis decided made new version of fog collector named CloudFisher (Image 09). The new version was aiming to solve the problem of fog collector maintenance due to high wind pressure, while not adding an extra level of complexity to the system, i.e. requiring more tools and components to install the collector.

Image 09. CloudFisher fog collectors ("CloudFisher", 2019)

The research results are 3D mesh system that can withstand the wind speed up to 120 km/h while it only requires two tools to install. In Image 10 (a) the mesh is visible with another layer of elastic grid behind it for extra support in high wind pressure, rather than connecting the mesh directly to the poles with rigid links, this system uses a cheap and replaceable rubber expanders that reduces the wind impact (Image 10 (b)). The efficiency of the system according to Aqualonis is 10-22 liters per square meter.

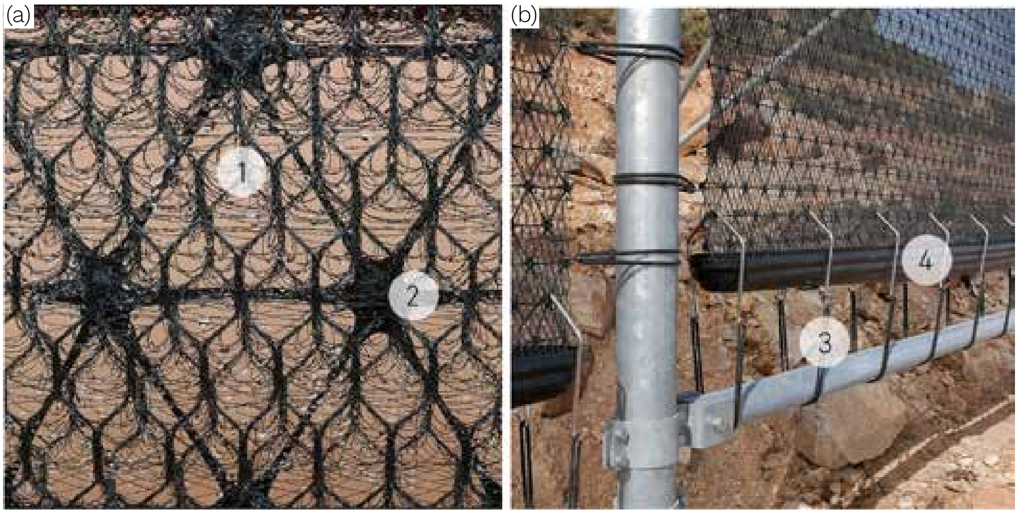


Image 10. (a) Mesh structure and supporting plastic grid behind it (b) Rubber expanders fixing the mesh to the poles ("CloudFisher", 2019)

3. <u>Mesh types</u>

Working principle of fog collector mesh is very simple, they are exposed to the moving fog by wind, some of the droplets inside the fog are then trapped between the mesh and when there are enough droplets they form a bigger droplets and move toward the bottom of the mesh where they are transferred to a reservoir tank.

Most commonly used type of the mesh for fog collector is Raschel shade net (Klemm et al., 2012. Rajaram et al., 2016. Batisha 2015) made by Chilean manufacturer. The material of Raschel net is food-safe Polyethylene and the net, when installed, forms many small stretched triangles (Image 10 (a)) facing the dominant wind and harvest the water and increase the water droplets run-off. Such net can be placed as double or single layer, although double layer results in better yields since two layers movements against each other make the run-off process easier (Klemm et al., 2012).

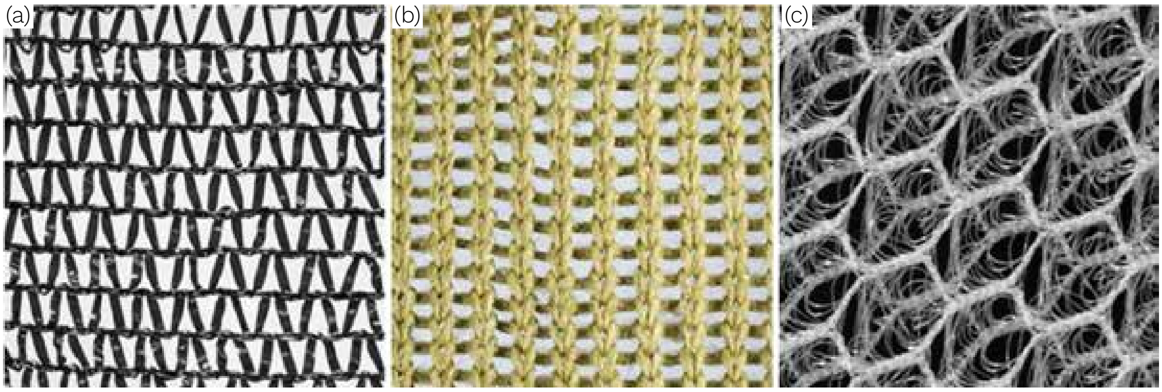


Image 11. (a) single layer Raschel mesh (b) stainless steel mesh with poly material (c) poly materials (Klemm et al.,2012)

Raschel mesh is the cheapest and most available mesh type for fog harvesting, although it is not without a downfall, for example it is not robust enough to withstand the strong winds therefore in sites with extreme conditions it's advised to use more robust material for mesh such as stainless steel (image 11(b)).

There are also research comparing the standard double layer 35% shade Raschel mesh to other types of mesh such as metal mesh and other textile (Image 12). The results showed that the Raschel mesh is not the best fog harvesting material; although it performed better in low wind speed (less than 1 m s-1) with collecting difference of 160% more than FogHa-Tin but in wind speed greater than 5 m s-1 it collected 45% less. Overall the MIT-14 stainless steel mesh collected 3% more in low wind speed and 41% more in higher wind speed (Fernandez et al., 2018).

Although the Stainless steel mesh performs better when compared to other mesh materials the Fernandez study concluded that due to cost factors (i.e. several hundred for stainless steel compared to pennies per square meter of Raschel mesh) and weight of the mesh which requires better supporting structure, the Raschel mesh is still the best choice for Fog collectors. As for FogHa-Tin compared to Raschel, the cost difference is still too much (15 times more to be exact) hence the favirouble choice still remains to be the Raschel mesh for fog collectors.

Image 12. (a) Raschel mesh 35% shadecloth (b) metal mesh coated with POSS-PEMA (c) FogHa-Tin, a 3-D spacer textile (d) the rotated version of the FogHa-Tin textile (Fernandez et al., 2018)

It is worth mentioning that Raschel mesh can also be improved to yield more and harvest more water, study done by Rajaram found that by using a superhydrophobic coating, the mesh will yield 50% more and by further enhancements of the geometry of the mesh resulting in easier droplet fall down the yield can be increased by another 50%; at the end of the study they concluded that the improved mesh will collected water ~2 times that of typical Raschel mesh (Rajaram et al., 2016). Although the improvements are very considerable there is no information available regarding the cost implication of applying such changes and improvements to existing Raschel mesh

3. Water Quality

Fog collector's water qualities are similar to dew collectors, since both devices are prone to collect the aerosol particles that are already existing in the site. The water droplets will wash off the particles that are already collected on the surfaces of the mesh and store it in the water tank. This might not be a problem in most of the sites, data collected from fog collectors in sites including El Tofo in Chile, Ashinhaib in Oman and Namib Desert near Gobabeb all showed the quality of the water is within the World Health Organization (WHO) limits(Klemm et al., 2012).

But there are also cases (in coastal of Chile) that the water quality were below the standard with high concentration of ions and metal in the water (Starter et al., 2010 cited in Klemm et al., 2012) due to particles in the air from power plant emission nearby. Overall, harvested fog water are considered safe but if there is a potential of contamination, the water quality should be checked or the harvested water needs to be treated before consumption.

Section Summary:

In summary Fog collectors yield depends on fog liquid water content i.e. type and frequency of fog and geological position, the size and arrangement of the mesh material and types, collecting methods of the fog droplets along with the wind speed.

Advantages	Disadvantages
• Low-tech • Low cost / cost-effective • Passive - no need for an external energy source • Portable • Also collects rainwater	• High maintenance - if the sites has extreme weather e.g. high wind speed • Expert force is required to maintain the system • Requires a supervision during high wind conditions • Low water quality • Further treatment and filtration is needed to make the water drinkable • Site specific and seasonal

Variables

- Fog type, intensity and frequency of fog aqurance
- Elevation and geological position
- Wind speed
- Mesh size, type, geometry and material
- Maintenance and available force or trained personnel to maintain the fog collector in extreme weather
- Shape of the collector in correlation to wind speed and fog direction
- Cost factors including the material, installation and maintenance

2.1.3 Nature and biomimetic collection methods

In nature many species including plants, insects and animals learned to adapt themselves to harsh arid regions where there is little to none available water to drink. They evolved to take advantage of the moisture in the air and collect water with the help of the nanostructure on their skin, leaves or spikes. In fact, these systems are so effective that scientists around the world are taking note of them and more research is done to unlock the mystery behind their efficiency so that they can help improve the existing AWG systems.

Following sections will go through different species of plants, insects and animals and their method of collecting water from air. Finally the example of biomimetic collectors that are based on those design methods are reviewed.

Before diving into different water collecting methods in nature, it will be beneficial to address the basics and terminologies that are repeatedly used in the following sections when talking about the water droplets behaviour on different surfaces and collecting methods.

The behaviour of a surface in relation to water droplets can be explained by two terms: (a) **Hydrophilic** or (b) **Hydrophobic**. Hydrophilic surface do not repel the water, they would rather pin the water droplets on their surfaces, in other words they tend to absorb water; opposite to this behaviour is hydrophobic surfaces where they repel the water and in a way becoming waterproof.

If a single drop of liquid sits on a surface with a contact angle greater than 90 degrees the surface is hydrophobic and if the angle is less than 90 degrees the surface is hydrophilic with good wetting properties (Fig 09).

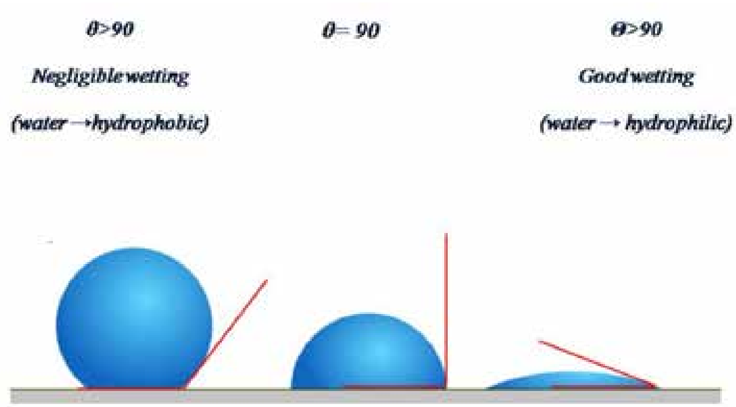


Fig 09. Water droplet angle and surface properties. (“Contact Angle platform | FMPS - Functional Materials and Photonics Structures”, 2019)

Furthermore if the contact angle is more than 150 degrees the surface is considered superhydrophobic and any additional water that come in contact with initial water droplet will form a ball type droplet and if less than 5 degrees the surface is considered superhydrophilic, when additional water is added the water will start to even out and cover the surface.

When the water droplet contact the surface it can be in one of the following two states: Wenzel state or Casie-Baxeter state. , Wenzel state the droplet is pinned and in full contact with the surface (Fig 10 (a)) in Casie-Baxter state is where the droplet is sitting on the air trapped between the solid surface and the droplet (Fig 10 (b)) The surface properties (i.e. being a hydrophilic or hydrophobic) can be amplified by changing the surface roughness and using topography that enhance Wenzel or Casie-Baxter state. (Darmanin and Guittard, 2015)

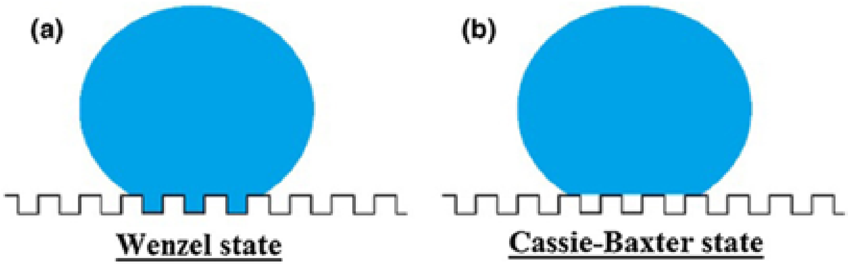


Fig 10. Water droplet in (a) Wenzel state (b) Cassie-Baxter state (Darmanin and Guittard, 2015)

Water collecting and repelling methods in Plants

Plants leaf and in case of cactus, spikes are evolved to capture water from air moisture (fog or dew). But repelling water is as important as collecting it, in many plants and even on animal skins the combination of hydrophobic and hydrophilic properties has been observed (later in this section example of such behavior is studied and presented in detail) this is due to having a more effective system in collecting and directing water to the roots. Due to this reason both hydrophobic and hydrophilic surfaces are studied through following sections,one famous example of such surface is Lotus leaves which are superhydrophobic surfaces that repels the water droplets effectively.

List of plants harvesting water from moist air:

- Stipagrostis sabulicola (Namib Bushman grass): Capture Fog (Andrew et al., 2011; cited in Sharma et al., 2016)
- Cactus species such as Opuntia microdasys: Fog (Ju et al., 2012; cited in Sharma et al., 2016)
- Bermuda grass such as Cyondon dactylon: Fog (Sharma et al., 2016)
- Dryopteris marginata: Fog (Sharma et al., 2018)
- Eremopyrum Orientale: Fog (Gursoy et al., 2017)
- Cotula fallax in South Africa: Fog (Klein, 2019)

Main character of **lotus** leaves are having a water contact angle greater than 150 degrees which make them superhydrophobic, ultra low water adhesion and self cleaning properties are other characteristics of their leaves Darmanin and Guittard, 2015). Lotus leaves repel the water to avoid mold formation and better photosynthesis by cleaning the dust off the surface, this kind of self-cleaning and superhydrophobic properties of the lotus leaf is known as “Lotus effect” (Nosonovsky & Bhushan, 2008 cited in Zhang, Feng, Wang & Zheng, 2016). This effect is happening due to multi-scale structure of lotus leaf which combines micro-papillae (with a diameter of 5 micro m to 9 micro m presented in image 13) and nano hairs (with diameters of 120 nm) along with special type of wax to trap the air pocket under the water droplet so the water only interact with the tip of the rough surface and the underlying surface stays dry.

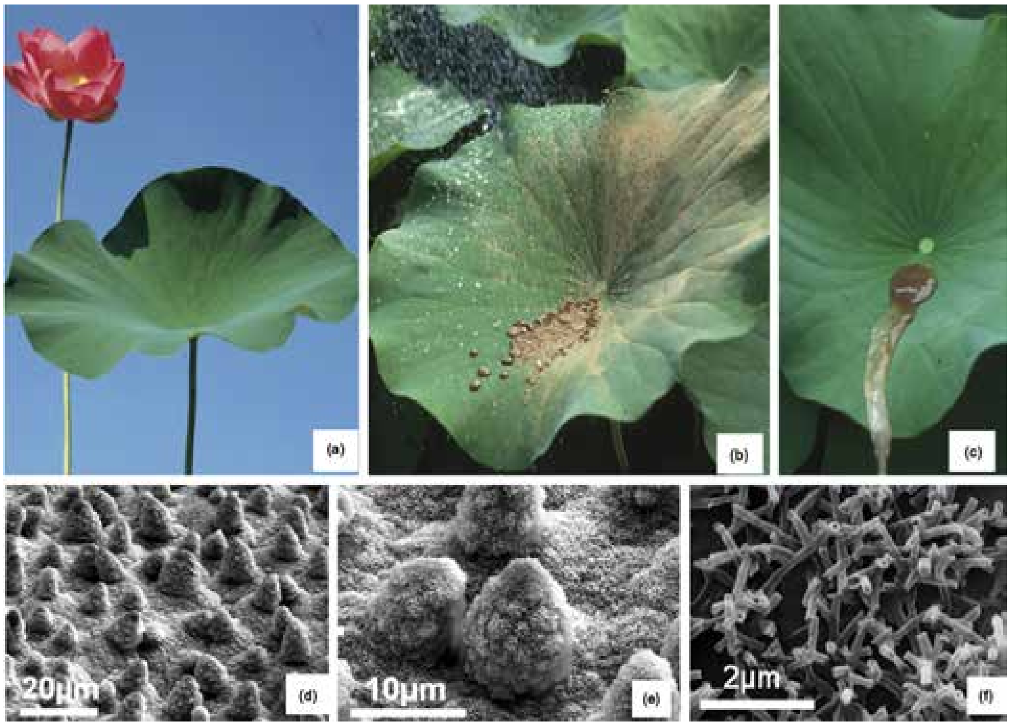


Image 13. Superhydrophobic lotus leaves (b-c) self-cleaning properties derived from Cassie-Baxter state (d) micro and nano surface structure (e) convex cell papilla at microscale (f) epicuticular wax at nanoscale (Darmanin and Guittard, 2015)

All the above properties of lotus leaves results in a very high contact angle of the droplet (the microscopic angle approaches 180 degrees) leading to superhydrophobic behavior in Cassie-Baxter state that assists rolling effect of the water droplets on a lotus leaf.

Salvinia molesta is another interesting example, on its surface it has microscopic eggbeater structure (fig 17 (b)). Such structure is hydrophilic, since it pines the water droplets while traping the air under it resulting in keeping the leaf surface dry. Since this plant sometimes will submerge in the water for weeks such surface properties will trap the air and make a layer of gas separating the water from the leaf and keep the surface dry even under the water.

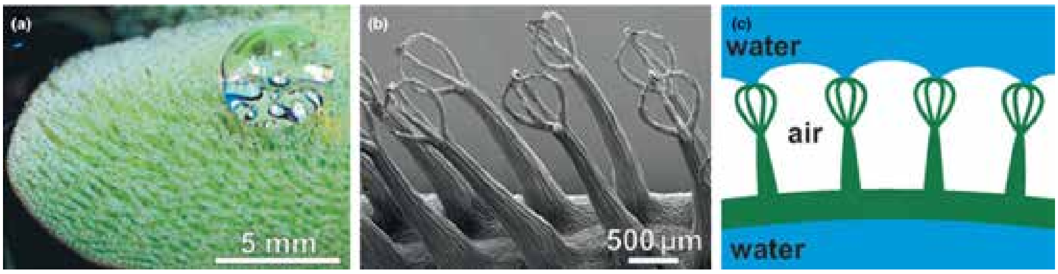


Fig 11. Salvinia molesta leaf and its magnified structure (Darmanin and Guittard, 2015)

The lotus effect is not just limited to lotus, other plants and animals such as rice lead, salvinia molesta, butterfly wings, mosquito eyes, fish scales and shark skin also shows similar properties of lotus leaf (Fig 12).

Fig 11. Lotus effects in other species (Zhang, Feng, Wang & Zheng, 2016)

In a similar method to fog collector system the surface of the water collecting area (in plants and insects) will not get wet the water droplet start condensing on the surface and make droplet deposition (Falconer et al., 1980; Schemenauer and Cereceda,1994). Such process of collecting water is critical for survivability of the plants and animals in arid to semi arid areas, plants such as Alchemilla mollis, Echeveria, Lupin regalis and Euphorbia as reported in Shirtcliffe et al. all show combination of superhydrophobic areas (mostly in their leaves) and highly hydrophilic areas with clear difference in roughness and surface structure, the superhydrophobic areas first pin the droplets on the surface (same method as the Salvinia molesta) and after the droplet mass becomes critical it rolls on the surface toward the stem or the mouth of the insect with help of micro hydrophilic groves channeling the water. (Darmanin and Guittard, 2015)

In arid to semid-arid areas, plants have learned to adapt and survive the drought by harnessing the water vapor in the fog or collect the moisture as a dew with the help of their leaves. Study done by Vogel et., al 2011 collected and studied dew plants in Namaqualand in South Africa that survive based on the water they collect from the dew or fog. Image 14 is an example of such plants collected in the study.

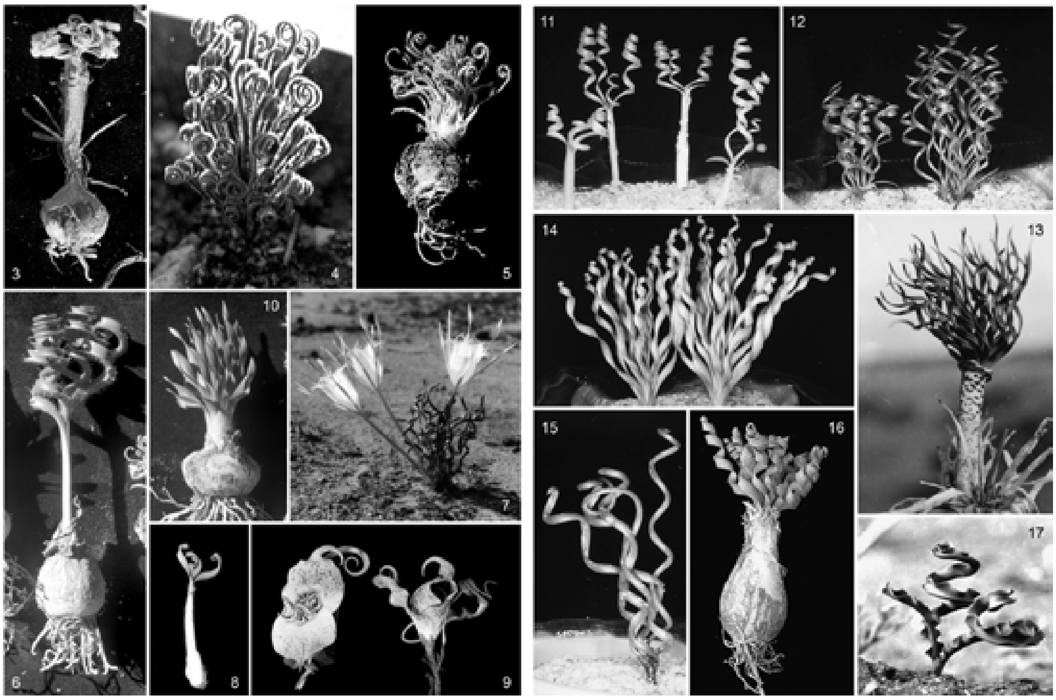


Image 14. Different types of plants that collect water from fog (Vogel et al., 2011)

According to their study dew mostly forms on the leaf edges or even along with the single hair on the plants, this happens at night where there is a clear sky at a high level of humidity. Clear sky helps the IR radiation stored in plants and earth escape at a faster rate to the sky and bring the leaf surface temperature closer to dew point i.e. cooling down the surface at a faster rate.

In their observation they also mentioned that upper leaf surface condenses more dew than underside, this is due to the soil or land under the plant emitting heat and therefore the temperature is higher under the leaf compared to upper leaf surface, also If the plant has a dense stand, it will collect less dew, this is due to the fact that they store heat for longer time compared to single isolated plants (Walles, 1993 cited in Vogel et al., 2011).

Exact amount of dew collected by different plants in Namaqualand desert is unknown to the researchers since some plants absorb the water directly from their leaves and some pass the droplets to the soil underneath them, they determined the importance of the plants leaf shape in collecting dew and tried to mimic the shape of different plants (Image 15) in the lab to determine their capability in collecting dew, but due to the complexity of making a dew chamber they made a fog chamber and tested the metallic leafs accordingly.

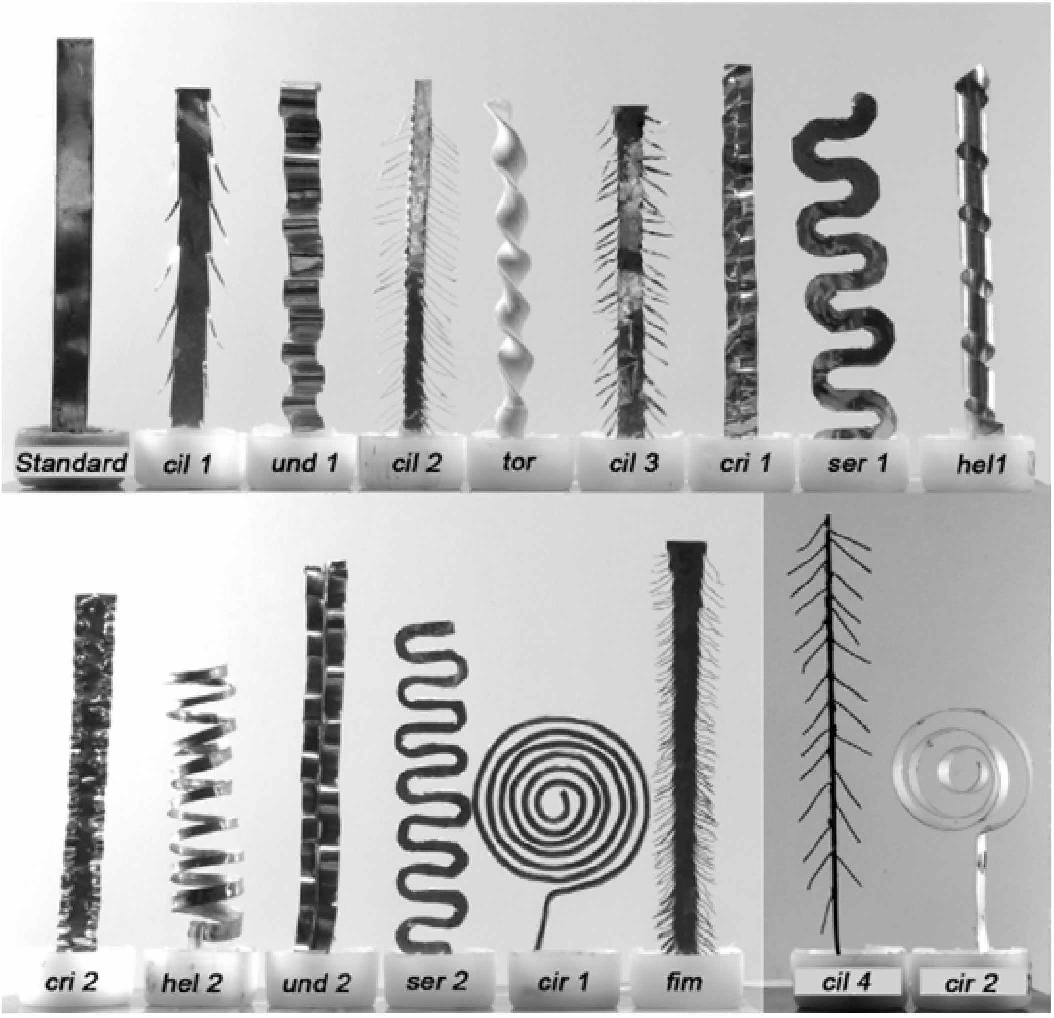


Image 15. Model made and used in fog drip experiments. (Vogel et al., 2011)

All fourteen test subjects were put into the fog chamber and the tests were repeated 10 times to compensate for uneven pressure in fog jet stream, the results are presented in Table 03. The best results for collecting water were established for Film 1 with 66% water collection and Cir 1 with 54%.

Model	cil 1	und 1	cil 2	tor	cil 3	cri 1	ser 1	hel1	cri 2	hel 2	und 2	ser 2	cir 1	fim 1
%	0.1	3.2	3.7	6.0	6.7	12.9	16.7	19.3	21.0	22.0	23.9	24.0	54.0	66.0
Confidence	0.989n.s.	0.553n.s.	0.242n.s.	0.527n.s.	0.231n.s.	0.46*	0.281n.s.	0.12*	0.000***	0.002**	0.000***	0.000***	0.000***	0.000***
Edges	0.47	0.20	0.36	0.17	0.45	0.25	0.40	0.21	0.36	0.28	0.31	0.59	1.89	0.92

Table 03. Mean amounts of water collected by 14 types of models in % of surplus over respective standard water harvests after 10 min exposition to artificial fog during 10 sessions per model; (T-test * degree of confidence). (Vogel et al., 2011)

The results suggest that a surface with uneven structures and sharp edges will assists the water collection process (Vogel et al., 2011), they also found that adding small wire (26 pieces of 10mm long and 0.5 mm thick wire) to a flat plate increase the yield to 66%, this finding is inline with finding from Gursory et., al 2017 research group, they studied Salsola crassa plant where its natural habitats are in arid climate and it survives by capturing water droplets from fog.

Image 16 shows how the growth of water droplet starts from the hair attached to the plants and how the hair (2-5mm long) helps the leaf to remain superhydrophobic (Image 16 a), this effect becomes visible when the hair is removed (Image 16 b) and contact angle of the droplet reduces to 25°, resulting in leaf wetting and hydrophilic properties. (Gursoy et al., 2017).

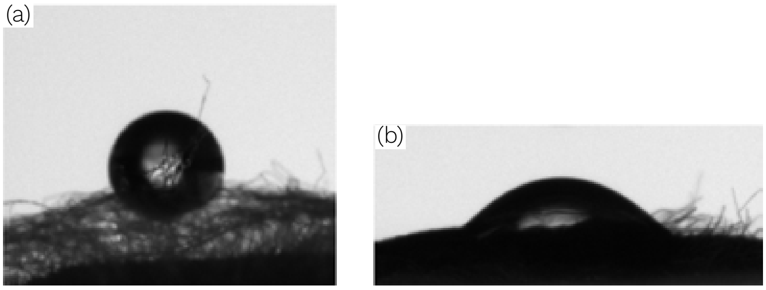


Image 16. Water droplet contact angle images of Salsola crassa plant leaf: (a) 169° with hairs; and (b) 25° without hairs (Gursoy et al., 2017)

Cynodon dactylon is a Bermuda grass (Image 17 a-d) that can be found any several regions originated from the Middle East and can be found in several areas of semi-arid and arid areas of the world, it has certain surface structures that assist the deposition and growth of water droplets along with transporting them and collecting them.

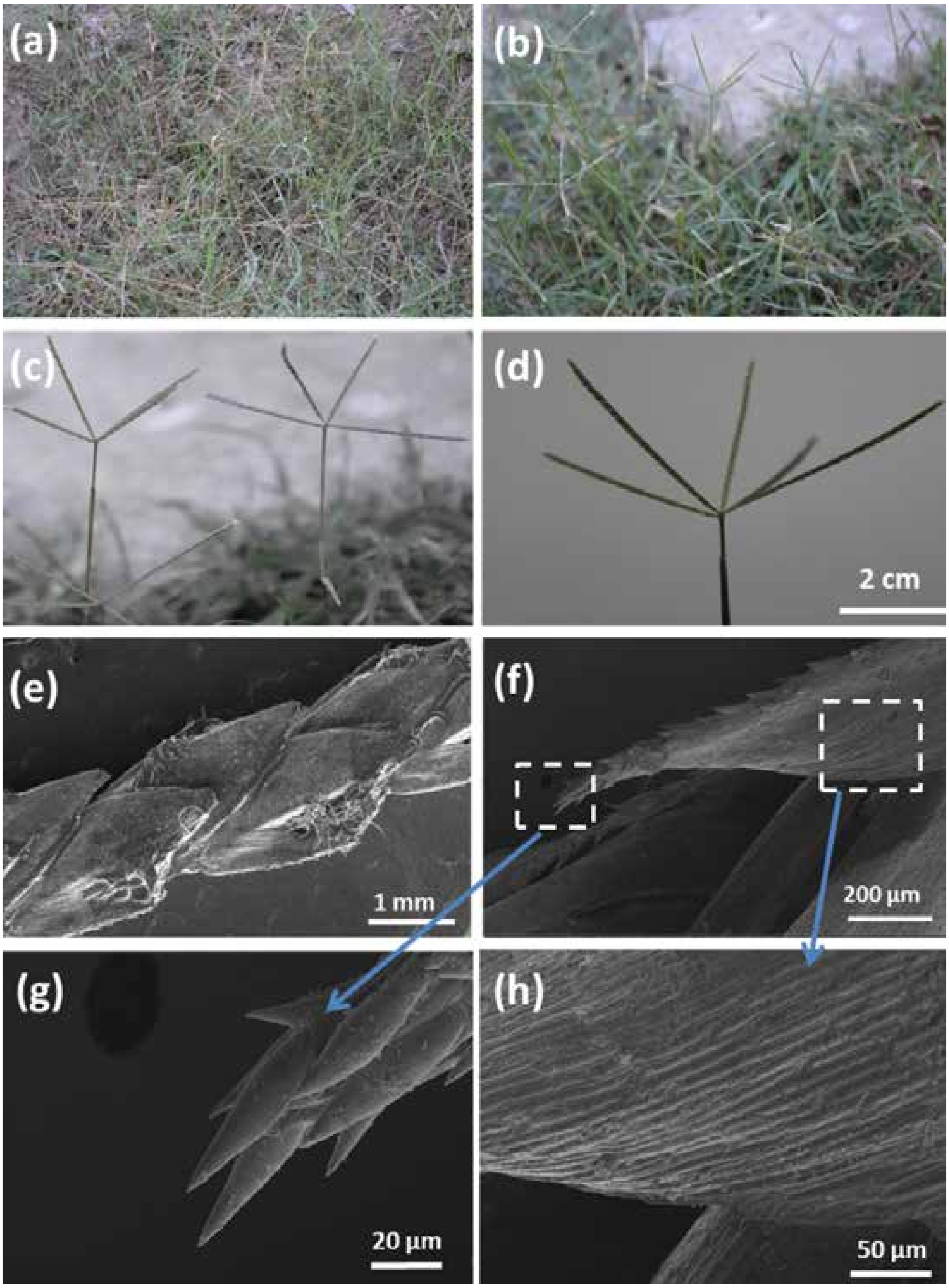


Image 17. Cynodon dactylon: (a and b) Photographs in its natural habitat, (c and d) Images of spikes arranged in the whorl, (e and f) SEM Images showing the microstructures (g and h) magnified image of spikes having conical spine clusters and gradient grooves, respectively. (Sharma et al., 2016)

Scanning electron microscopy (SEM) was used to observe the individual spike (Fig Image 17 e-h), the outer part of the grass contains the leaf blades (4 cm long and 4 cm broad) with sharp tip and rough edges, the upper part of has inflorescence like spikes (4 cm long) each spike further divided into two different structure: i. Flattened surface with gradient groves (Image 17 h) ii. The cluster of spines with conical shape arranged in and ~15° (Image 17 g) (Sharma et al., 2016).

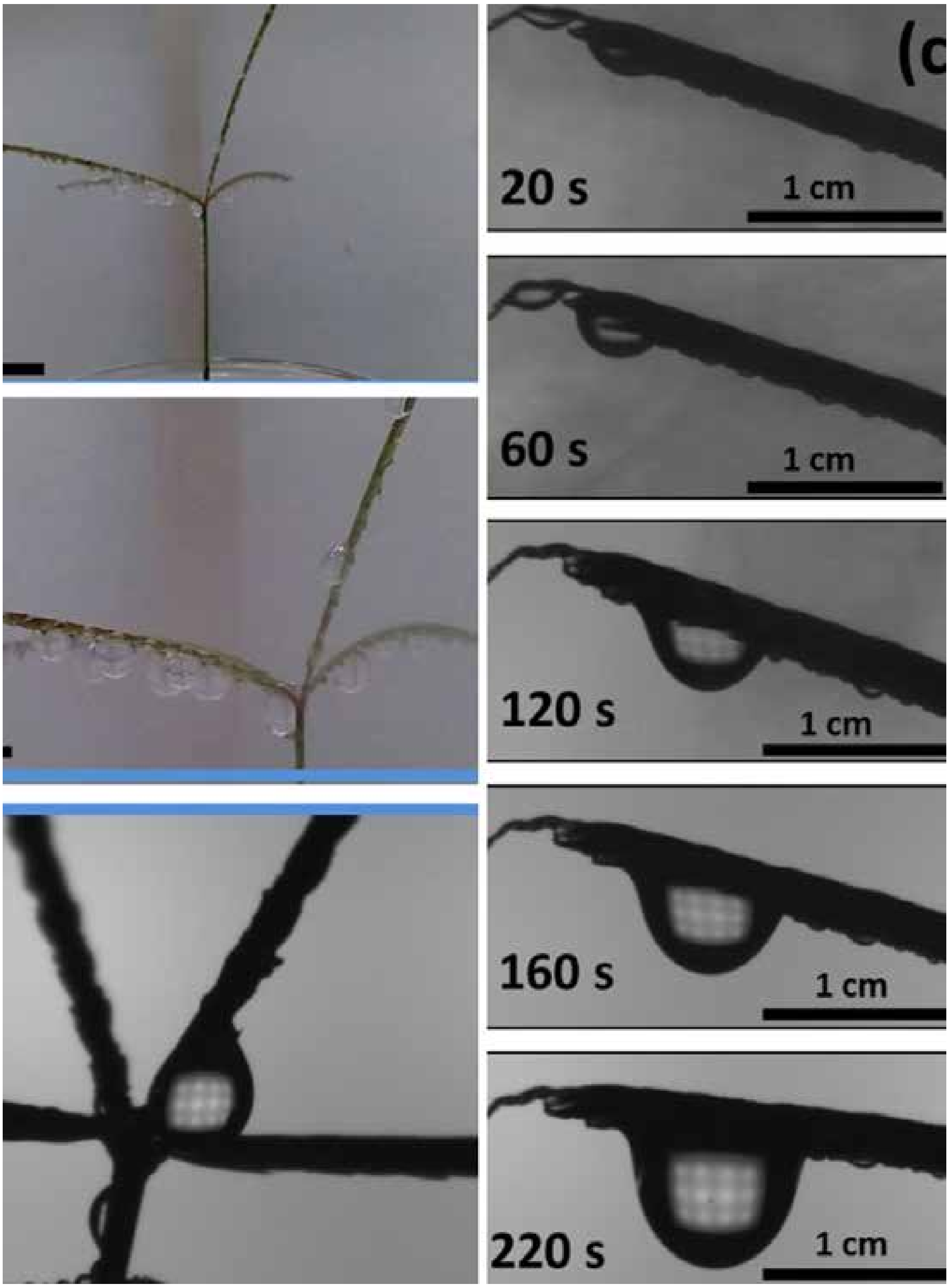


Image 18. In situ optical observation of the droplets on spikes of Cynodon dactylon: (a) photographs of droplet deposition and hanging on the fiber-like spikes, (b) water droplet collected at the base of the whorl transported through the grooves on the spikes and (c) process of initial droplet deposition and growth on the spike as a function of time. (Sharma et al., 2016)rma et al., 2016)

Image 18 shows the droplet deposition, growth and movement. Different shape and construction of the leaf blades (conical spine cluster and flatten structure with gradient grooves) leads to water deposition at the conical spines and the droplet starts rolling toward the spine and gradient groves after the droplet size become critical, this process repeats itself and is not influenced by the angle of the leaf.

The force corresponding to the movement of the droplet from the spike towards the base of the leaf and plant are Laplace pressure gradient. The droplet start moving from smaller radius toward a larger radius due to Laplace pressure gradient (Laurenceau 2004, cited in Sharma et al., 2011), due to the pressure difference within the water droplet at the tip of the spine (smaller radius at the top) and base of the spine (bigger radius) the driving force is initiated which leads to the droplet movement from the tip to the base.

Dryopteris marginata is a species originated from arid areas of Himalayan regions of India, China, Bhutan, Nepal and Northern Burma, Tibet and Yunnan (Puri et al., cited in Sharma et al., 2018), the majority of the plants in arid to semi-arid areas has different and complex structure for collecting the moisture but the factor that sometimes is missing totally is the water transportation after the collection process, transporting the water with the highest efficiency is also as important as collecting it. Dryopteris marginata is one of the plants with very high efficiency of collecting and transporting the fog water. What makes the D.marginata interesting is its multiscale channels on the surface of its leaves, they help to spread and transporting the collected water very efficiently. (Sharma et al., 2018)

D. marginata has a wide triangular shape and widely truncated base ~65 x 25 cm, there are 15-20 pairs of pinnae ~25 x 6.5 cm which they are further divided into 15 lobes ~6 x 2.5 cm (Image 19). All of this structure has a remarkable ability in directing the water rapidly downward as well as sideways toward the ape of the main blade and from there to the apex of the pinna where gravity assists the further transportation of the water.

Image 19. Dryopteris marginata fern (Sharma et al., 2018)

Same as the previously discussed plant's D.marginata has a complex microstructure that results in efficient water collection. SEM scan is done by Sharma et al., 2018 research team, shows two main structures on Pinnule, (i) ridge-like structure that is positioned at the central part of pinnule and runs to the tip with width of 5-15 micro m, they run parallel to each other and assisting the water transportation and overall efficiency of the process (Image 20 b) (ii) further investigation showed semicircular grooves (Image 20 c) which they feed the water to the central channel. Similar to the main channels and ridges at the centre of the pinnule, there are smaller and narrow channels positioned at the side of the apex.

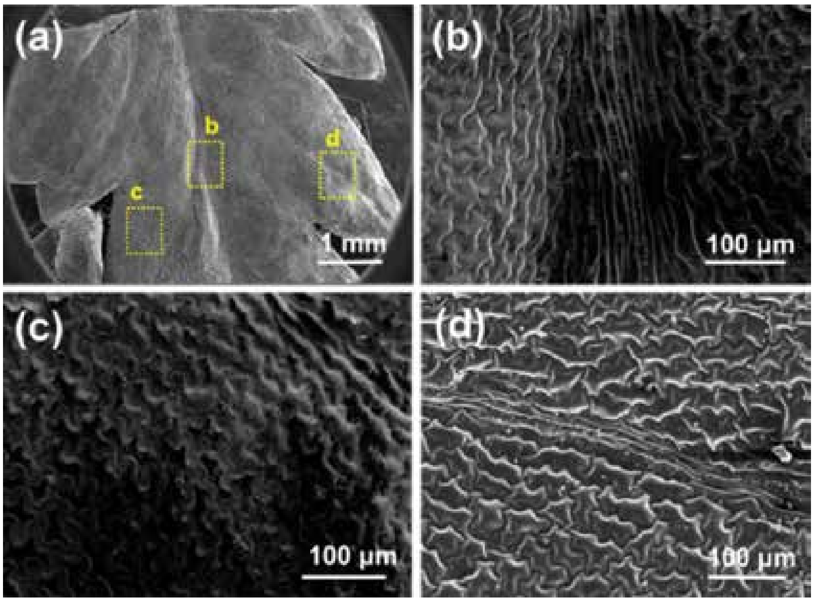


Image 20. SEM of D. marginata leaf (a) the apex (b) main channel (c) semicircular channels (d) side channels (Sharma et al., 2018)

After the moisture in the air are collided and captured on the surface due to condensation, the water droplets will be directed and channelled along the length of the leaf toward the ground (Fig 26) this feature is due to microstructures, both semicircular grooves and microchannels at pinnula and pinna.

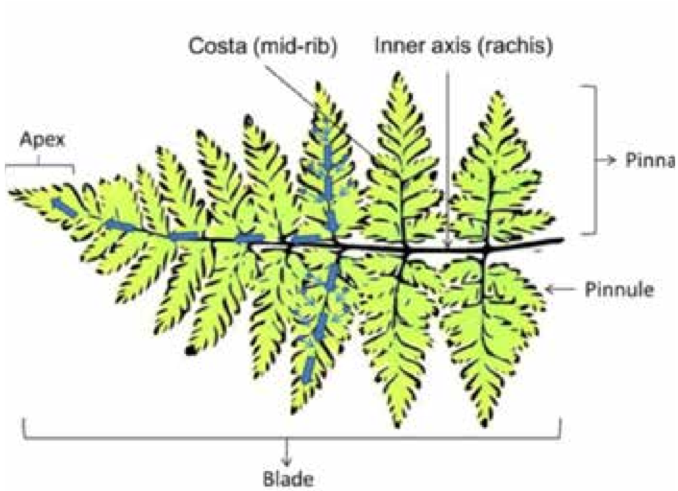


Image 20. Fern lead and water direction (Sharma et al., 2018)

Cactus species such as Opuntia microdasys were studied for their fog-harvesting properties which has efficient water transportation system using clusters of trichomes and conical spines arranged on the cactus stem (Ju et al., 2012 cited in Sharma et al., 2018)

O. microdasys originates from Chihuahua desert and it has integrated multiscale and multifunctional system to collect fog efficiently. Image 21 a-b shows the plant structure, with bundle of spines positioned on the stem apart from each other at a distance of ~7-23 mm, each of this cluster has a trichomes at the base (Fig 26 c and d, dotted line) with ~100 spines on top with an average angle of 18.1 ° ± 5.3 ° forming hemispherical structure. Using SEM showed each spine has three different levels of structure, **(i)** oriented barbs (Image 21 e,h) **(ii)** gradient grooves in the middle (Image 21 f,g) **(iii)** trichomes at the base.

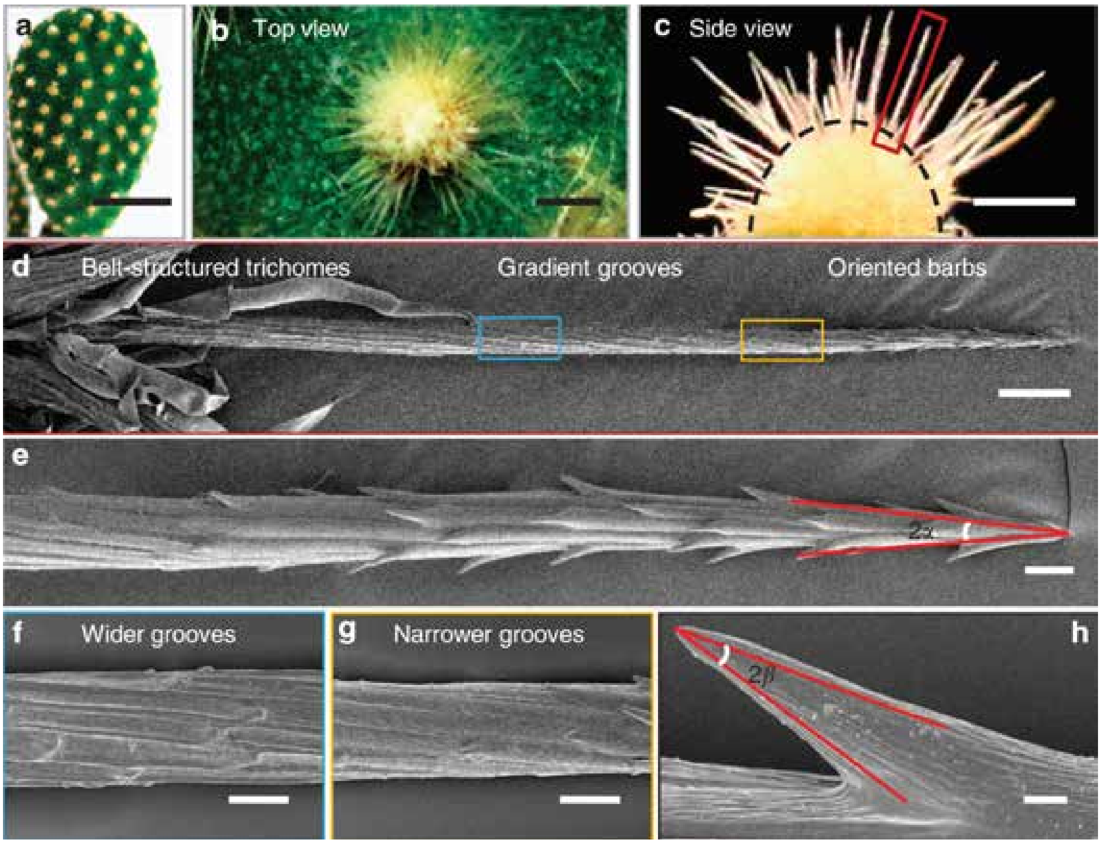


Image 21. (a) Image of O. microdasys (b) magnified image of the spine cluster (c) cluster of spines growing from trichomes (d,e) SEM image of single spine (f) magnified image of the region near the base and the tip of the spine (h) magnified image of single barb (Ju et al., 2012)

Initial research indicated that the first deposition and formation of the water droplets happens on the tip of the spine where there are barbs (Image 22) these tiny droplets moves toward the base of the barb and forms a bigger droplets through times where other or same barb keep collecting and feeding the same droplet. The main reason for the tendency of the droplet movement toward the base of the barb is the available gradient Laplace pressure between the two sides.
The collected droplets at the base of the barbs become visible and grow in size in a matter of seconds and start moving toward the base of the spine while joining and forming bigger droplets (Image 22 b). In this case the driving force behind the movement of the water droplets from the tip to the base of the spine is the gradient of surface-free energy and gradient of the Laplace pressure. At the end of the spine all the water is collected in the areas where it is covered with trichomes. (Ju et al., 2012)

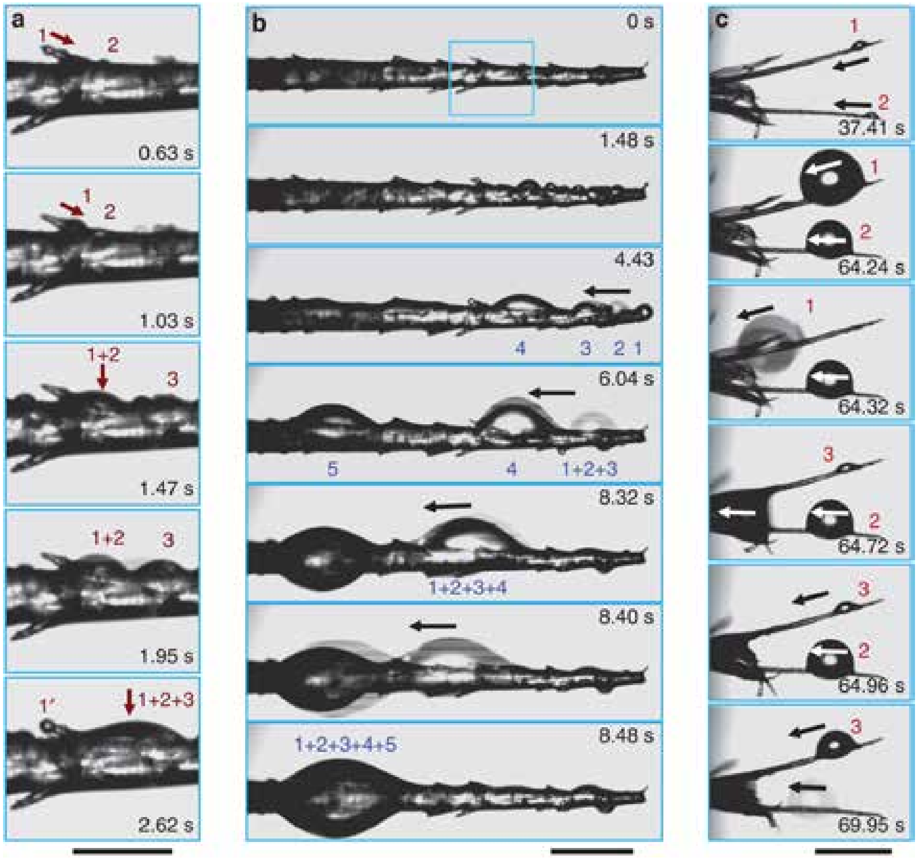


Image 22. (a) water deposition on the tip of the spin and barb (b) water deposition and movement on the spine (c) water behavior on two separate spine (Ju et al., 2012)

Other factors that leads to water deposition and the movements of the water droplets is conical shape of the spine and the placement of trichomes at its base, such shapes leads to presence of strong capillary force i.e. when there is water in in trichomes the strong force rapidly absorb the water in. This process of absorbing the water as fast as possible (27 seconds of generating and transporting compared to 0,5 second of absorption) is critical for initiating new cycle of water collection. (Ju et al., 2012).

<u>Summary:</u> The water droplets initially forms at the tip of the spine where there are barbs, the water droplets grow in size at the base of the barbs and later start moving toward the base of the spine due to the presence of gradient groves on the spine, conical shape and gradient of surface and Laplace pressure. At the base of the spine the trichomes assist the absorption by providing strong capillary forces where it prepares the spine for new cycle of water collection with fast absorption Fig 12 a.

Similar to Cynodon dactylon bermuda grass, the Laplace pressure gradient is due to radius differences in the conical shaped spine where the driving force will push the water droplet from smaller diameter where the pressure is higher (the tip) to the larger diameter where there is less pressure (base of the spine) this is illustrated in Fig 12 b.

Other force that drives the water droplet movement is gradient surface free energy. This is mainly due to gradient of roughness in the spine, where the surface of the spine becomes smother at the base and rough close to the tip (Fig 12 c). This results in having different water contact angle and making different surface properties where the tip becomes hydrophobic and the base becomes hydrophilic. This difference of characteristics is another driving force behind the movement of the droplets to the base of the spine.

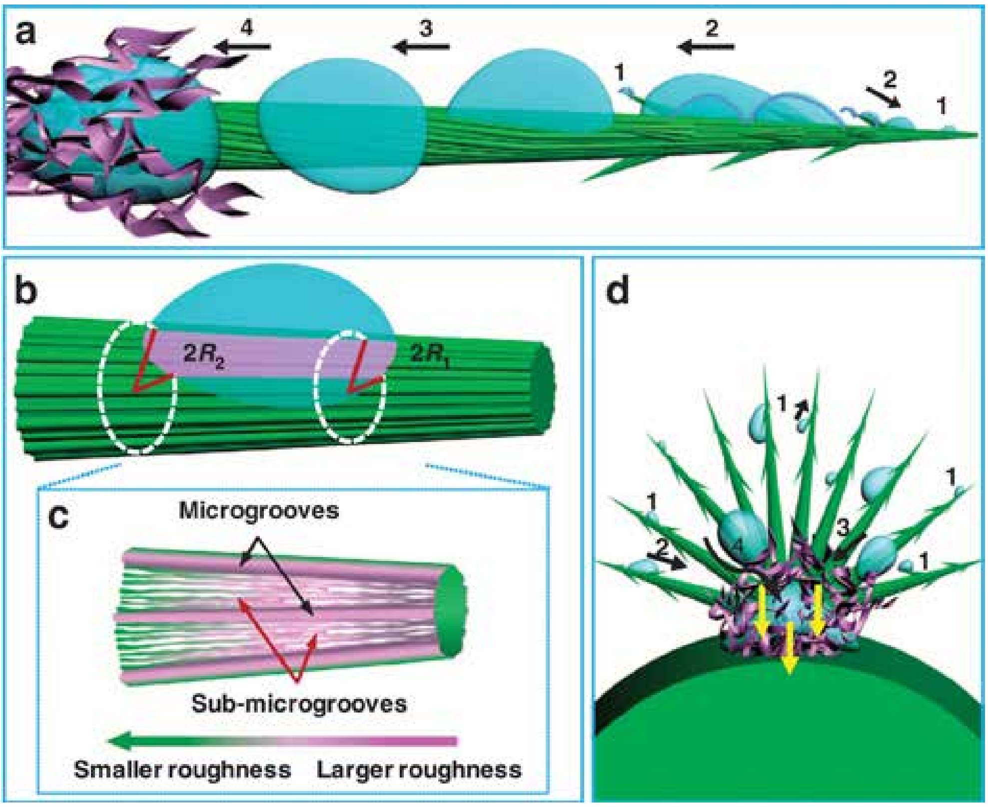


Fig 12. (a) summary of water collection and absorption of O. microdasys single spine (b) driving force behind the water movement (c) gradient microgrooves on the spine making gradient roughness on the spine (d) overview of multiple spine and the process of water collection and absorption (Ju et al., 2012)

Water collecting and repelling methods in Insects

In nature, in the same way as the plants, insects learned to adapt and survive in arid and semi-arid areas of the planet. Few examples of such animals and insects are listed as follows:

Animals and insects collecting water from moist air:

- Uloborus walkenaerius spider silk (with the help of naturally occurring spindle knots and joints in their fibre): collecting Fog water (Zheng et al., 2010; cited in Sharma et al., 2016)
- Beetle in Namib desert: collecting fog water from their body and directing the collected water to their mouth.
- Lizards such as Moloch horridus, Phrynocephalus arabicus and Phrynosoma cornutum: collect the moisture from the air with the help of honeycomb micro ornamentation on the outer surface and complex capillary system in between. (Effertz et al., 2011 cited in Sharma et al., 2018)

Beetles in Namib desert: One of the best examples of fog and dew harvesting in nature can be found in some beetle species living in the Namib desert in Africa. In both cases of beetles either collecting dew or fog, they use their body surfaces (elytra) which consists of complex nano and microstructure with different hydrophobic and hydrophilic properties for condensing and transporting the water to their mouth (Parker & Lawrence, 2001 cited in Sharma et al., 2018).

Dew condensation capability of the **Physasterna cribripes** (Tenebrionidae) beetle (fig 30) was studied in the condensation chamber by Guadarrama-Cetina et al., 2014. There is a clear difference between dew condensation and fog-basking (when the beetle adopt a headstand posture facing toward the wind to collect water from the fog and run the collected water to their mouth, this behaviour is termed fog-basking (Hamilton et al., 1976 cited in Nørgaard & Dacke, 2010) , the way that the beetle is presented in the research is so that they tilt their body to 23° facing their elytra fused fore-wings (elytra) towards the wind and with the help of mixed wettability surface properties (smooth, with groves and bump) they collect water and after the droplets reaches the critical size it starts to roll towards the insect mouth.

But it is also possible that the same surface can or is used for dew condensation, since the natural habitats of such insects favour the dew condensation i.e. it has a clear sky (only six rainy days in the year 2013) which helps the infra-red to escape at a faster rate, high humidity with dewy night of more than 60% for the year 2013; also the elytra structure and placement (having no temperature regulation and elytra are disconnected for the body with a layer of air which add an insulation layer) favour the dew formation.

Image 23. Female Physasterna cribripes (Tenebrionidae), scale bar is 4 mm. (Guadarrama-Cetina et al., 2014)

Surface characteristics of the beetle is explained in Image 24 schematics were the outer surfaces of elytra with its valleys and bumps are present. The structure has a periodic bumps and hexagonal pattern with valleys and bumps, it is also coated with a layer of wax but the amount varies between the valleys and the bump resulting in different wettability properties of the surfaces.

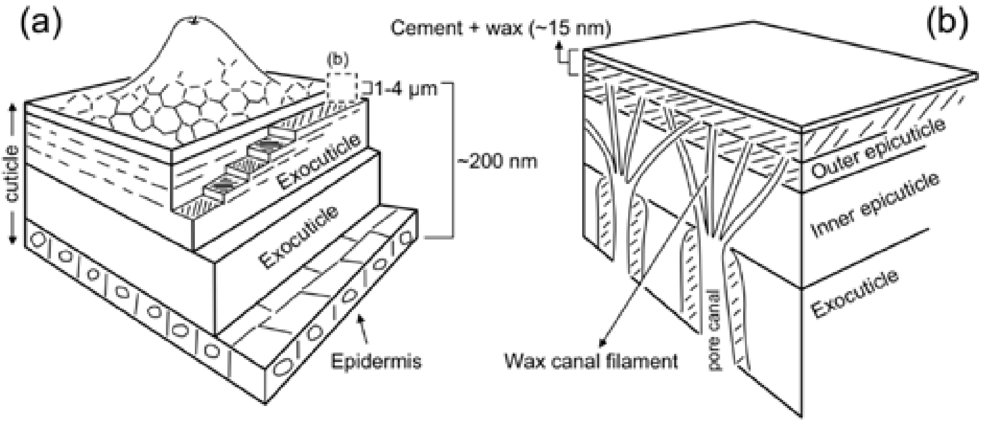


Image 24. Female Physasterna cribripes (Tenebrionidae), scale bar is 4 mm. (Guadarrama-Cetina et al., 2014)

One important surface characteristic for dew formation is IR emissivity, the results from the test in Guadarrama-Cetina shows that the beetle elytra surface has a very high IR emissivity with a rate very close to the glass (Glass: 1 and elytra: 0,95). This finding further supports the capability of the elytra in condensing water as dew.

Elytra was placed in a condensation chamber and the dew formation was observed, the observation is mainly focused on the area where the bumps and the valleys are positioned (Image 25).

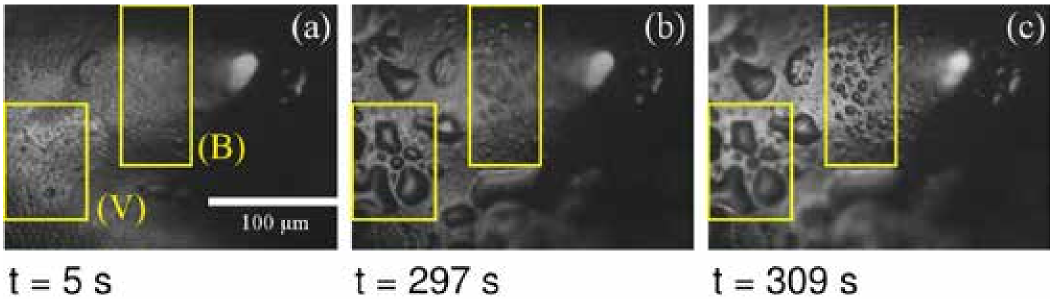


Image 25. Drop surface measurement of the elytra in the condensation chamber in Valley (V) and bump (B) areas. (Guadarrama-Cetina et al., 2014)

The results shows that most of the dew or droplets are formed in the valleys due to the geometrical (hexagonal microstructure and pattern presented in Image 26) characteristics of the valley and more area for the nucleation rather than on the bumps.

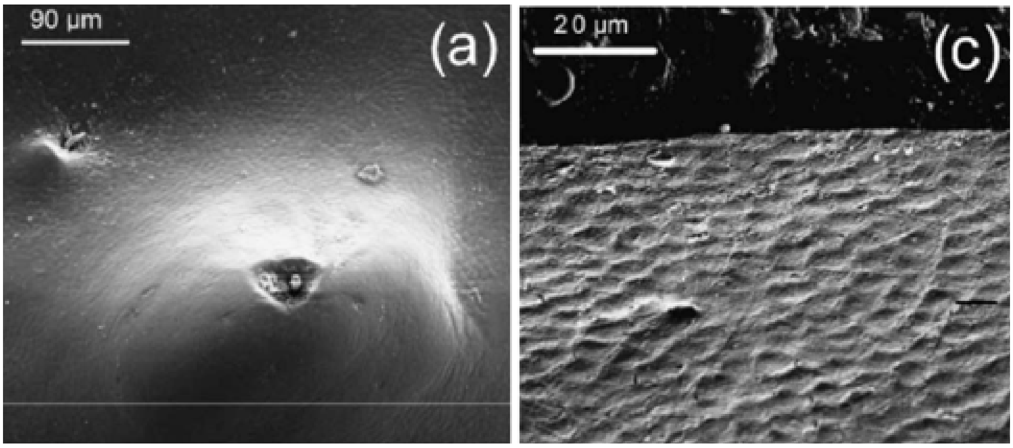


Image 26. SEM scan of elytra (a) bump with valleys around it (b) hexagonal surface structure of the valley. (Guadarrama-Cetina et al., 2014)

<u>Summary:</u> the Physasterna cribripes is able to collect dew because of its high IR emissivity and its elytra surface characteristics such as the bumps and valleys, especially the valleys are important for collecting the dew since most of the water collection happens within this area, it's surface structure with special hexagonal microstructure and patterns plays an important role in collecting the dew. (Guadarrama-Cetina et al., 2014)

There are many Darkling beetles (Tenebrionidae) that harvest water from fog in arid to semiarid Namib desert of Africa (Seely et al., 2005 cited in Norgaard et al., 2010) , although all achieve the same goal but they have different elytra surface structure, some such as genus Onymacris has smooth elytra surface other species are covered with bump (as explained in previous section). To resolve this a research done by Norgaard and Dacke, studied four different Namib desert beetles; Onymacris unguicularis and O. laeviceps (smooth elytra) and Stenocara gracilipes and Physaterna cribripes (bumpy elytra), all presented in Image 27.

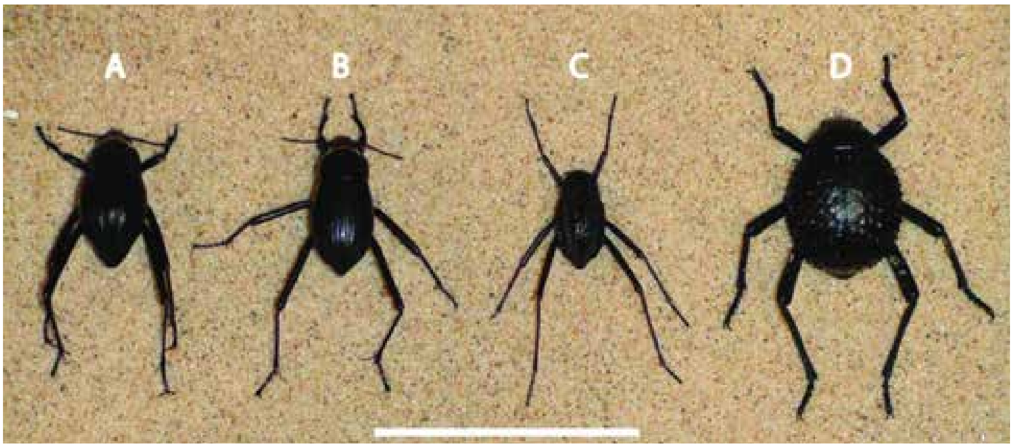


Image 27. Four types of tenebrionid beetle: (a) Onymacris unguicularis with wide groves and smooth dorsal surface (b) Onymacris laeviceps with similar surface as O. unguicularis with fine groves (c) Stenocara gracilipes (d) Physterna cribripes with regular array of smooth bumps. (Nørgaard & Dacke, 2010)

Previously based on Parker and Lawrence research (Parker & Lawrence, 2001) it was concluded that hydrophilic peaks surrounded by hydrophobic ridges (fig 33) are the main reasons for collecting water from the fog, since the water from the fog is settled on the smooth surface of the bump and later after the droplets size become critical it starts rolling down towards the head. But such result and conclusion are now questioned since there are many other beetles that actively collect fog water in nature such as O. bicolor and O. unguicularis with completely smooth elytra surface and regular grooves.

Elytra surface and its role for producing water is the main focus of Norgaard and Dacke research, SEM images of four different beetles (Image 27) with different surface structure are taken and studied (Image 28). The difference is very clear, O. unguicularis and O. laeviceps (Image 28 A and B) are both having a smooth surface with difference in the finesse of the grooves, opposite to those two beetles the S. gracilipes and P. cribripes both have jagged bumps that make irregular lines and rows positioned all over the elytra (Image 28 C and D).

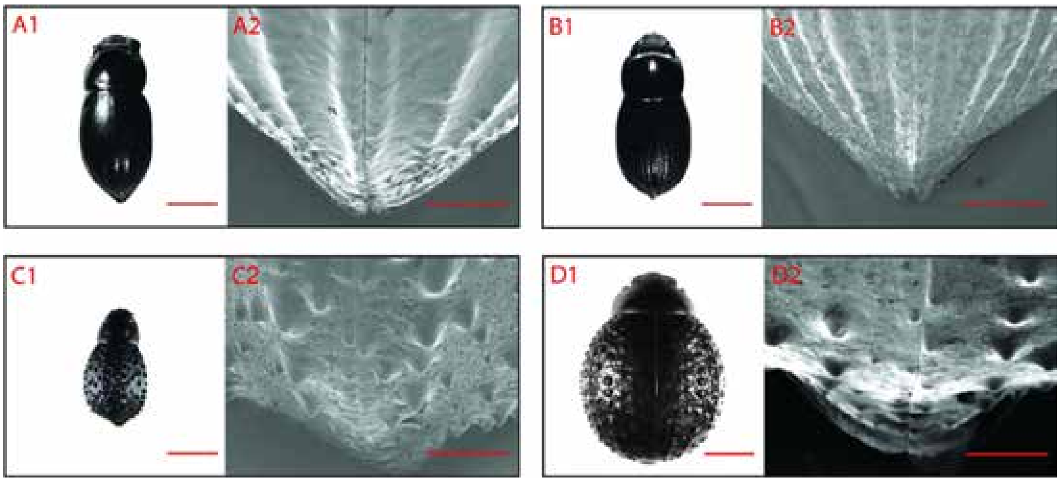


Image 28. SEM photos of four beetle species elytra: (A) Onymacris unguicularis (B) Onymacris laeviceps (C) Stenocara gracilipes (d) Physterna cribripes. Scale bar= 5 mm. (Nørgaard & Dacke, 2010)

To determine the water harvestation capability of the test subjects, they were put in the fog chamber for two hours each with fog-basking position (23° tilt with their back facing toward the fog), and the collected water were measured (Fig 13). The results show small variances between the beetles collected water and it was concluded that they all collected the same amount of water over a two hour period (fig 13 blue bars) but due to the size differences of the Beatles (Image 27) the collected amount were normalized accordingly based on the surface area and an estimate of the water collection efficiency of each species independent of their sizes (fig 13 red bars).

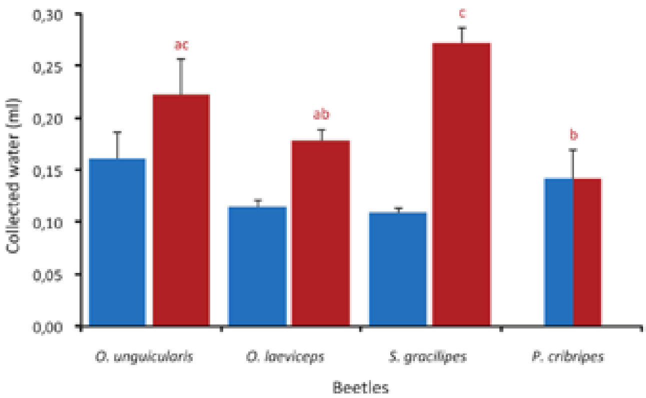


Fig 13. Fog harvesting efficiency of four beetles during two hours in a fog chamber. Blue bar: total amount of water capture by each beetle. Red bar: water collection efficiency based on the relative dorsal surface area of each beetle. (Nørgaard & Dacke, 2010)

The results show that O. Unguicularis beetle got some great results in collecting water, this is interesting since this beetle has a elytra surface that doesn't have any bumps or structure that are assumed to be assisting the process of fog harvesting and it doesn't show great differences (unlike S. gracilipes) when the water harvesting efficiency per surface area of the elytra is considered.

After the water collection rate and amount were corrected according to beetle size, the results shows that O.unguicularis with smooth surface and grooves along with S. gracilipes with bumps and irregular surface are the most efficient fog water harvester. Also the high efficiency of the O. unguicularis can be linked to its size, since smaller size in plants and insects can favour the harvesting process (whether fog or dew collection) due to easier heat exchange and assisting the air flow rather than forcing it go around the structure, this hypothesis is confirmed when the water collection efficiency per unit area of the biggest beetle in the list (P. cribripes) is the worst and least efficient among four tested species with smaller size.

<u>Summary:</u> Namib desert beetles learned to adapt to longer arid season by using the fog water as an alternative source of water. Before it was assumed that only certain type of beetle with certain structure on their elytra (bumpy and irregular macrostructure) are equipped to harvest water, but recent studies shows other factors such as the size of the beetle along with the physical characteristic while harvesting the fog or fog-basking (23° tilt of the body, with head down and back towards the wind and fog) can further assist the water collection. It is also clear that elytra surface with smooth grooves are also very capable and as efficient as the bumby hydrophobic elytra surfaces for collecting water from fog.

Other Water collecting methods

In previous sections the importance of surface properties (hydrophobic, hydrophilic and gradient wettability) in relation to water harvesting ability of the plants and insects are studied in details, but in what way can this information be applied in the real world?

New research done by Seo et al., 2016 studied Copper pipe for harvesting the moisture from fog and in the form of dew, what makes the study interesting is that different type of coating with different level of wettability has been applied to the pipe to obtain hydrophobic or superhydrophobic coating on the pipe surface. The results shows how such coating can be used to enhance the water collection yield for different purposes i.e. fog or dew harvesting application.

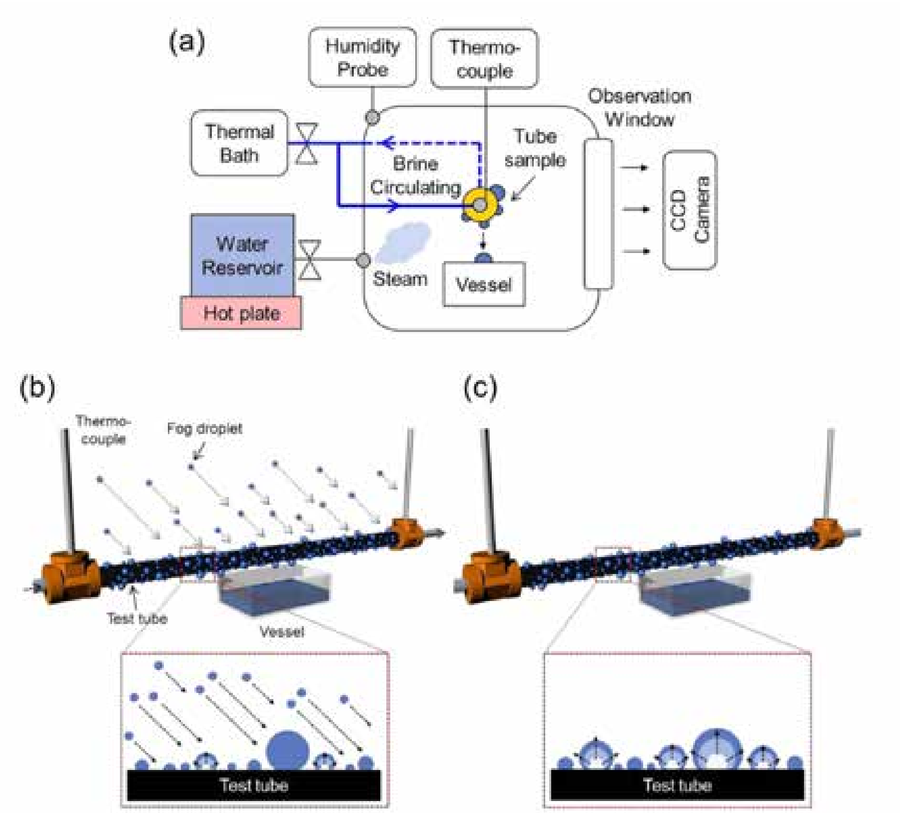


Fig 14. Water harvesting setup (b) fog harvesting chamber with water vapour stream (c) dew harvesting chamber without water vapour stream (Seo et al., 2016)

Fig 14 is presenting the testing procedure for fog and dew, fig 14 (b) is a fog harvesting method in which the copper pipe has a cool brine from a thermal bath inside it, fig 14 (c) is dew harvesting chamber which has the same setup as fog chamber with difference of not having a stream of vapour in the chamber. The temperature in the chamber is 35 °C for fog chamber and 40 °C for dew chamber with relative humidity of 90-99%.

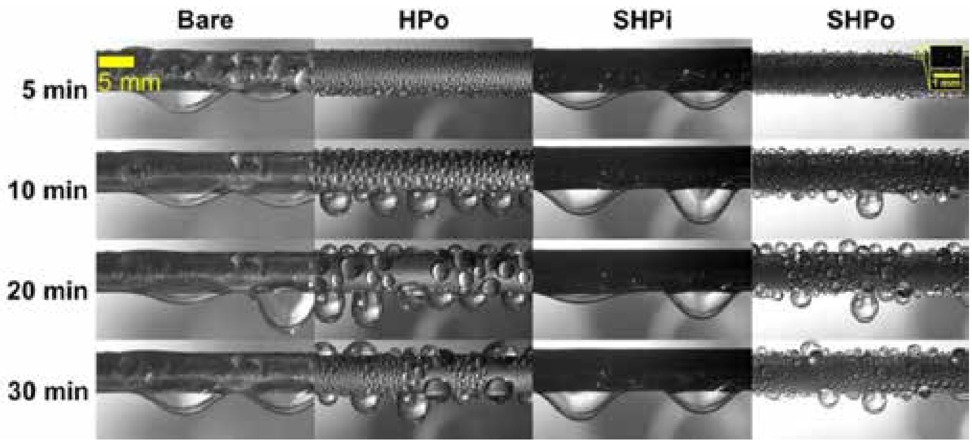


Image 29. Time-lapse of fog harvesting on copper with different coating and level of wettability (Seo et al., 2016)

Different coating was tested in the study, as presented in Image 29 Bare is the normal copper pipe, Hpo is hydrophobic, SHPi is oil infused superhydrophobic and SHPo superhydrophobic surface. Result of study for dew and fog harvesting is presented in Fig 15.

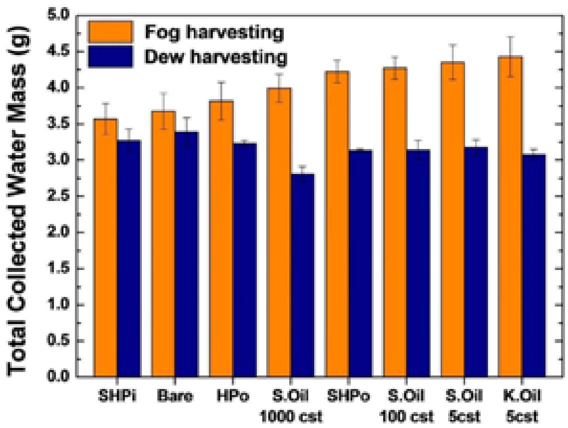


Fig 15. Total amount of collected water during 90 minutes in fog and dew chamber (Seo et al., 2016)

<u>Summary:</u> Results from the study shows that the best way of collecting dew is having wettable surface such as Bare and SHPi, furthermore the water removal efficiency has profound effect on system yield (Seo et al., 2016).

2.2 AWG summary and comparison

Atmospheric Water Generator can be categorized into two different types:

I. **Active**

Active AWGs are the types that require external energy source to do the condensation process, Heat pump systems are an example of such systems, in this system the moist air is sucked in and with the help of other components (e.g. compressor that uses the refrigerant gas, condenser, thermal valve/capillary tube and evaporato) and use of electricity it cools down a surface with an aim of bringing the surface temperature below the dew point and condense the water from the moist air.

Other methods for condensing water vapours on the surface using a heat pump involves usage of a subaerial heat sink for transferring the heat from the cooled surface into ambient air, a submarine heat sink using deep ocean cold water for transporting the sensible heat away from the moist air and use of underground heat sink.

II. **Passive**

Passive atmospheric water generators are systems that condes water from moist air (in the form of fog or dew) without any external energy input, example of such systems are fog and radiative cooling collectors. This systems are very site specific and their yields also varies depending on the location but they are easier to build, maintain and less complex; with additional advantages of being a low cost project compared to active AWGs.

2.2.1 AWGs operating variables

For each of the mentioned systems there are certain variables that should be met for optimum yield and results. Figure 16 is summarising the important variables for each system, in the middle there is an area which lists a number of factors that are shared between all three types of AWGs.

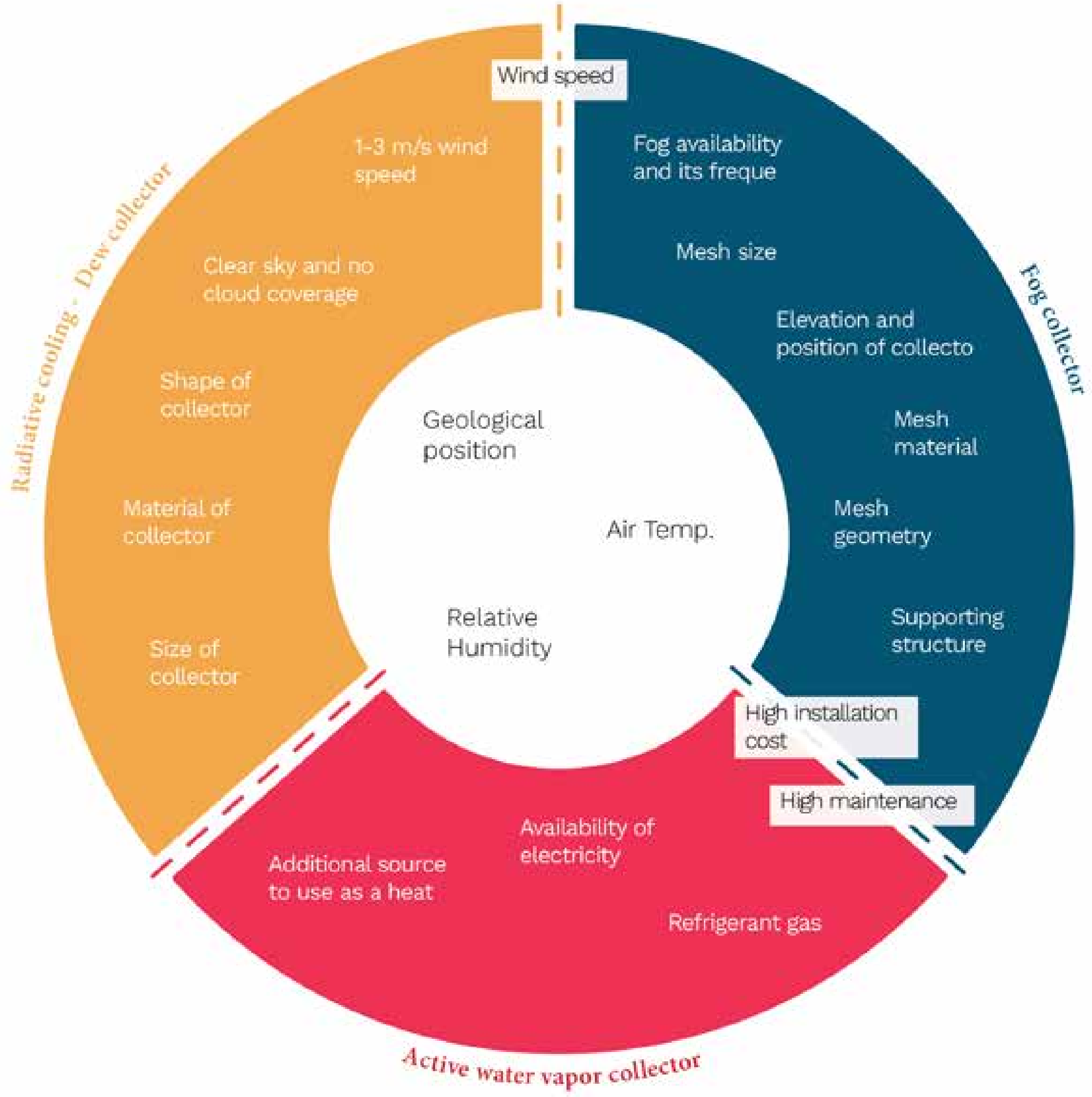


Fig 16. AWGs operating variables

Shared factors between all three types of AWGs are as follow: The necessity and availability of high percentage of Relative Humidity (RH) in the air, air temperature and the geological position of the generator.

All three factors are in a way linked to each other, Relative Humidity is an amount water particle (presented in percentage) air can hold at a certain temperature, in general, the hot air can hold more water particles than cold air therefore when RH is 90% in 34 °C and 90% in 24 °C the amount of water that is in hotter temperature is substantially higher. Therefore the hot and high RH is an idle condition for AWGs for producing more water out of the air.

This brings us to the third shared factor which is geological position, for example the fog collectors are mainly dependent on the presence and frequency of a certain type of fog in the region where they are installed, fog happens when the RH is 100% and the air can not hold more water inside, hence the saturation of water in the form of fog, this happens when the wind forced up the warm air over a mountain and force the warm air to interact with cooler air which results in the water condensation and fog formation, this change of phase happens due to natural topography change in mountains and valleys where the pressure and temperature change assist the fog formation.

If through the process of choosing the site for fog collector installation the global wind map and dominated wind pattern presented in the site along with topography that assist the phase change (i.e. land elevation in the form of hills or mountains) close to a large body of water or a source for high humidity is neglected the fog collector will not work and yield enough water.

Same explanation about geological position and its importance for the AWGs can be applied to Heat pump and Radiative cooling systems where each need specific conditions and train for optimum performance. For example Radiative cooling device need low wind (not greater than 4.4 m/s (Beysens, 2016)) with clear sky for assisting the IR transfer; Heat pump depending on the type and method of heat transfer need to have access to large body of water for submarine heat sink which uses a deep ocean cold water.

2.2.2 Positives and negatives of each system

For a more detailed comparison of each system positives and negatives of each system are presented in table ... while comparing and detailing the advantages and disadvantages of each system can be useful for assisting the selection process of AWG for specific site it can also clarify which system can be improved further in accordance with this thesis aim.

AWG types	Active	Passive	
	Heat pump	***Fog collector***	***Radiative cooling - Dew collector***
Advantages	. Well developed technology (Harriman 1990) . Availability of the components . Maintenance expertise fairly common (Wahlgren 2000)	. Low-tech . Low cost / cost-effective . Passive - no need for an external energy source . Portable . Also collects rainwater	. Low-tech . Affordable . Passive - no need for an external energy source . Portable . Can be used on rooftops to condense and collect dew water . Also collects rainwater
Disadvantages	. Harmful components such as Chlorodifluoromethane (CFCs) might be present in the system . High power consumption . Difficult to achieve even cooling of the incoming moist air (Wahlgren 2000) . Difficult to achieve dew point below 4.5 °C . Frost may reduce the performance and cooling process . High power requirement . Air filtration needs regular replacement	. High maintenance - if the sites has extreme weather e.g. high wind speed . Expert force is required to maintain the system . Requires a supervision during high wind conditions . Low water quality . Further treatment and filtration is needed to make the water drinkable . Site specific and seasonal	. Limited yield - 0.51 l /m2 . Larger areas or plants are needed to yield a higher amount of water . Low water quality . Further treatment and filtration is needed to make the water drinkable

Table 04. Different AWGs system advantages and disadvantages

1. **Heat pump and Active Atmospheric Water Vapour collectors**

Main advantages of such a system is that they are well developed and the components that are used in the system are also available in other applications (e.g. refrigerators and air conditioners) also the expert who maintain such devices are available and fairly common, this fact is only relevant if the device is installed in well developed areas and not in a remote place.

Other advantages include the size variance, there are many sizes available to choose from an office or home size that produce 25-50 liter/day to an industrial or military size devices that can produce over 900 liter/day with hefty price of 350,000 USD (“Genius Technology - Watergen”, 2019) (Image 30).

Also the water quality is very high, different filtration system (UV, air filtration and etc) that are in place for such systems make the condensed water the safest water for drinking and usage between all the other mentioned methods.

Image 30. Genny AWGs, (a) Genny home with water production of 30 liter/day and power consumption of 0,35kWh/liter, (b) GEN-350 with capability of 900 liter/day and maximum energy consumption of 10kWh (“Genius Technology - Watergen”, 2019)

Also it is worth mentioning that the condensation process of 1m3 of water from air requires an energy of 681kWh, this energy can be reduced by using other means such as use of natural heat sinks e.g. atmosphere or deep cold sea water, use of such methods are common and well developed. This can reduce the energy transfer amount as low as 2% (in the case of pumping sea water into the system) to 40-73% (in case of normal fan and refrigerant compressor) (Wahlgren 2001).

Disadvantages: heat pumps require high initial investment, (depending on the size and water production needs), high energy consumption and availability of electricity, regular maintenance (e.g. filter replacement) and presence of harmful refrigerant gas in the system. It is a complex system that requires an expert to monitor and maintain it.

2. **Fog collector**

Advantages: Fog collectors are low budget and low tech projects that provides fresh water from fog, they can be built in a way that implement local materials and involve locals for maintaining and running the collectors. They are mostly deployed and transported to arid to semi-arid areas where there is a frequent occurrence of fog, these places are often remote places on mountains or valleys close to large body of water (where it provides a humidity for fog formation) and the terrain provides the pressure and temperature change for fog to form.
Such system does not require any additional energy input and the whole process is passive.

Fog collectors are in use for more than half a century (first study done by Carlos Espinosa in Chile, 1957 (Gischler, 1991 cited in Holmes et al., 2015), during this time there are lots of data collected from different projects and sites that used fog collectors (list of projects and sites can be found in Table 02 and Fig 07), this data helped mapping a standard process and procedure for selecting the site, testing and using the fog collector.

One example of such a standard is a “Standard Fog Collector” which is 1m*1m mesh sitting on 2m high poles, this fog collector is standard in size and normally at the beginning of the project before deploying larger collectors, this standard version is first deployed to the test site for testing and knowing how much water it can be collected at that site and later on comparison is made between other sites around the world. All of this data and standardization helps the fog collectors to improve systematically in future.

<u>Disadvantages:</u> Certain types of fog (advection or orographic type) that are made due to high elevation are generally favored over other types of fog, this is due to the reason that those mentioned fog has a higher level of water content compared to the fog that are made on land or sea level; this important factor along with wind direction make the fog collectors site specific, i.e. they can only works at certain places if the specific requirement (e.g. fog type and wind direction) is met.

fog collectors are collecting water from the passing fog through the hanging mesh. The bigger the mesh the bigger the overall yield, in some cases the large fog collectors are 12m by 6m and 18 m2 of flat panel rasched Fog collector mesh. The problem comes when the mesh is hanging between two supporting poles without much support for the mesh itself, since high wind situation is not uncommon in fog collectors site (wind speed greater than 17 m/s will cause some level of destruction on existing collectors) there will come a case that the wind storm speed goes higher than the mesh limit and destroys the mesh (Lastra et al., 2002 cited in Holmes et al., 2015)

After the collector net is destroyed locals can not fix them due to lack of expertise and hence the project stops all together. Therefore it can be concluded that one of the main disadvantages of fog collector is not being designed for high wind situation.

Other negative points of fog collectors are their water quality, they are prone to collecting aerosol particles that are already existing in the site and store them in their tank. Although in most cases the collected water was within WHO limits there are still concerns about the quality of the collected water. (Klemm et al., 2012)

3. **<u>Radiative cooling - Dew collectors</u>**

<u>Advantages:</u> the main advantage of the Dew collectors is that they are lightweight and cheap; they can be transported easily to the desired site, since the main component is a lightweight film made of Polyethylene embedded with microspheres of TiO_2 and $BaSO_4$ (PETB). This film can be placed on top of another supporting structure, a ditch in the ground or a rooftop of a house (Image 02).

Dew collector as explained above are low tech solutions, they don’t need an external energy source (e.g. electricity) to work and they are completely passive. Other advantages of the system is that due to their shape and material used for condensing dew droplets,make the rain collection process much easier and hence the device can also be used for collecting rainwater.

<u>Disadvantages:</u> Dew collectors have very limited and low yield of water (0.05 - 0,6 liter/m2 per night) and one way of increasing the yield is to increase the surface area, normally this can be achieved simply by placing the PE films on top of the roofs, but if there is a need for water in remote areas that do not have any infrastructure and the supporting structure should be built, then this solution is not viable anymore.
Same as fog collectors, dew collectors are also collecting the aerosol particles and store them in the tank, if the water is used for drinking they should be filtered and treated before drinking.

2.2.3 Other factors

Along with the factors mentioned above, two other important factors decides the viability of AWG system. These factors are; the **yield** (water production capability) and **cost** (cost of producing a liter of water per day) of the system.

1. **Yield**

I. Active water vapour systems:
Table 05 is summarising the yield of Heat pump and active water vapour collector. Heat pump has high water production compared to other systems, the version mentioned here is an office/home based version that is one of the smallest version of active systems which works with fan, refrigerant compressor and pump. As explained in the previous sections, there are many types of such devices and their yield varies depending on that, e.g.The Rainmaker makes 25 L/day (Wahlgren, 2001), Geny home and office version makes 15-20 L/day with power consumption of 330 Wh/l and GEN-350 makes 450 L/day with power consumption of 300 Wh/liter and total power requirement of 5.8 kW ("Genius Technology - Watergen", 2019). Table 0 is summarizing the projects and device using refrigerant coolant and other heat pump method of producing water and their relative yield per day, with and yield ranging between 9-3000 l/day.

	Name	Description	Yield
Devices	*Large*	large scale condensor	*~3000 l/d* *~125 l/H*
Devices	*Gen-350*	medium scale condensor	*~450 l/d* *~20 l/H*
Devices	*Genny*	small home and office condensor	*~15 l/d* *~0,7 l/H*
Projects	*ADS 1999 Rain maker*	small condensor	*25 l/d*
Projects	*Harrison 1998*	-	*9-18 l/d*
Projects	*Helstrom 1969*	-	*50-170 l/d*
Projects	*Seaewater Greenhouse*	Large condensor, Patton and Davis in 1996	*550 m3/d*

Table 05. Heat pump and AWVP projects and devices around the world and their water yield.

II. Fog collectors
Fog collector yields are also very dependent on size, their yield are normally justified per square meter of the mesh they have, the mentioned numbers in the table 06 are an average system yield in which the fog collectors around the world are collecting water per square meter during one day. It is common to use the average number of 5-6 L/m2 for calculating the yield of fog collectors during a year since there are days that the collectors collect over 10L (as presented in table 06) and days that are not collecting at all, hence the range between 3 - 12 l/m2 per day ("FogQuest: Sustainable Water Solutions", 2019; Calderon et al., 2010; Marzol et al., 2010; Klemm 2012).

Project	Description	Period of data collection	Refrence	Yield
Padre Hurtodo - Alto Patche	large scale fog collectors in Chile	14 years	Henderson et al ., 2001	***6 l/m2 per day***
Ecuador - Pachamama	high mountain region	2 years 1995-1997	Calderon et al., 2010 cited Klemm et al., 2012	***12 l/m2 per day***
South Africa	-	3 years 1995-1998	Klemm et al., 2012	***1-5 l/m2 per day***
Oman	mountain near Hajja in 2003	3 months in dry winter season	Schemenauer et al., 2004	***4,5 l/m2 per day***
Yemen	Asir region in 2010	3 months	Abualhamayel et al., 2010	***2 l/m2 per day***
Tenerif Island	Maderia station Bica de Cana	14 years	Marzol et al.,2010	***10 l/m2 per day***
North west of Africa	Boulaalam region	2 years since 2006	Marzol et al., 2008; Marzol et al.,2010	***1,9-7 l/m2 per day***
Croatia	mount velebit	unknown since 2000	Mileta et al., 2010	***4 l/m2 per day***

Table 06. Fog collector projects around the world with their yield per meter square of mesh.

III. <u>Passive Radiative collector or Dew collector:</u>
Dew yield is also dependent on the geological position, area and shape of the condenser but they are mainly limited by the amount of cooling energy that is transferred between the dew collector material and the atmosphere, the maximum amount of energy that can be transferred will not exceed 100 W m2 which leads to theoretical yield of 0.8 L/m2(Sharan et al., 2017) but this figure is yet to be achieved and the maximum reported collected dew is 0.6 L/m2 from a project in Jerusalem (Berkowicz et al., 2012 cited in Beysen et al., 2013).

Project	Description	Data collection period	Yield
India Kotahara	540 m2 off ground dew collector	12 months	***0,6 l/m2***
Israel Jerusalem	176 dew events in a year	12 months	***0,5 l/m2***
India Kotahara	12 units of 1m2 condensor	-	***0,05-0,55 l/m2***
India Suthari	343 m2 of roof condensor with 96 dew night in 2005 and 85 in2006.	2 years 2005-2006	***0,045-0,054 l/m2 1497 l/year***
India Sayara	360 m2 of roof condensor with 92 dew nights in 2005.	1 year 2005	***0,11 l/m2 3622 l/year***
India Panandhro	850 m2 of on ground condensor.	11 months 2007	***0,3 l/m2***
France Ajaccio island	3 m x 10 m of plane condensor	16 months 2000-2001	***0,38 l/m2***

Table 07. Dew collectors projects around the world with their yield per meter square of their surface area (mostly PE foil).

As mentioned previously dew yield is very dependent on geological parameters, geometry along with the size of the condenser, through the literature review (table 7) it is concluded that the yield of such systems are very limited and range between 0,05-0,6 l/m2 per night.

Summary: Table 08 is summarizing the findings and yield range of each AWG system, the conclusion from the collected data is that the active-heat pump solution provides the most water with range 9-3000 l/day (Table 05) (dependent on the size of the condenser and initial investment of the project/budget) and passive dew collectors provides the least with passive fog collector yield of 3-12 l/m2 (Table 06) (dependent on geological placement, size, type and design on mesh that collect the fog) and finally the dew collectors with range and yield of 0.05-0,6 l/m2 (Table 07) that is dependent on geological parameters, geometry, material and size of the condenser.

	Active-heat pump	Passive-Fog collector	Passive-Dew collector
Yield	9-3000 l/day	3-12 l/m2 per day	0,05 - 0,6 l/m2 per night

Table 08. AWGs water yield per day. Detailed information about the origin of the numbers can be found in table 05, table 06 and table 07.

The method of water production is the key to the yield amount, the major factor that affects the water production of the systems is the environment and conditions that they need to produce water, for example the Heat pump method will produce water from high RH air as long as the electricity is available but dew collector are dependent on natural factors such as clear sky, dew point, temperature, humidity, wind and so forth, all of these mentioned factors bring the water production window to few hours at midnight to early morning and hence affect the final result of the system. Same can be said about Fog collector where the frequency and availability of the fog is the main concern.

Some factor that is not considered in the above calculation is the rainwater, although the objective here is to compare the water production capability of each system it is important to mention that other sources of water such as rain water is completely ignored; rain water is an important source of water where the dew collector and fog collector (dew collector collects the rain water more efficiently than the fog collector) collects substantial amount of water at a site during a year but often such collection is not considered part of the system collected water.

2. Cost

There are many factors deciding and affecting the final cost of a liter of water produced by an AWG, each system has different variants, such factors are explained as follows.

I. Active water vapour systems:

Active systems are by far the most complex system between all the mentioned examples here, the initial cost of the system varies a lot (depending on the size, yield and method of condensation) in addition to the initial investment of the machine there are other costs such as electricity costs e.g. such devices use 270-550 kWh/m3 presented in table 09 (Wahlgren 2001) this number is verified by current devices in the marker such as Geny home and office version and GEN-350 with power consumption of 300-330 Wh/l and total power requirement of 5.8 kW (“Genius Technology - Watergen”, 2019). The additional electricity cost needs to be added to the final water cost and this of course varies depending on the electricity rate of the place it is being used.

Other factors such as maintenance (e.g. change of air filtration and other components changes), labour cost and lifespan of the device should be also considered in calculating the final water cost.

Method	Energy (kWh/m^3)	Proportion of minimum theoretical energy required (%)	Major energy use
AWVP: Seawater Greenhouse system (Paton and Davies, 1996)	2.6–6.3	0.4–0.9	Pumps and fans
AWVP: Condenser array cooled by deep cold seawater (Rajvanshi, 1981, p. 304)	15	2	Pumping seawater through system
Desalination (reverse osmosis) (Rajvanshi, 1981, p. 304)	**17**	**2185[a]**	**Pumping plus pressurizing feed water to 5400–6800 kPa (UN, 1985, p. 248)**
Desalination (multi-stage flash) (Rajvanshi, 1981, p. 304)	**83**	**10,668[a]**	**Seawater pumping plus heating of feed water (United Nations, 1985)**
AWVP: Refrigerating compressor (Harrison, 1996, 1998)	270–550	40–81	Fan, refrigerant compressor, water pump
AWVP: Refrigerating compressor (Meytsar, 1997)	322	47	Fan, refrigerant compressor, pump
AWVP: Refrigerating compressor (Kajiyama, 1974)	400	59	Fan, refrigerant compressor, water pump
AWVP: Refrigerating compressor The Rainmaker® (ADS, 1999)	480	70	Refrigerant compressor and fan
AWVP: Dehumidification technology (Hellström, 1969, p. 13)	500	73	Refrigerant compressor and fan
AWVP: Condensation by direct expansion of cooled compressed air (Meytsar, 1997)	1800	264	Air compressor, turbine, refrigerant compressor

[a]Proportion is with respect to 0.778 kWh/m^3; other values in column are with respect to 681 kWh/m^3 (Table 1).

Table 09. AWG - heat pump and desalination energy requirements for producing 1m3 of water. (Wahlgren 2001)

As mentioned above there are many variables that decides the water cost of a heat pump devices, but from literature review such devices are producing water at final cost of 12,24 USD/m3 of water or 0,012 USD/L (Wahlgren 2001) and from industries rate they produce 0,02-0,04 USD/L (watergen.com for GEN-350 and Gen home and office version).

II. <u>Fog collectors</u>

Factors that decides the collected water costs for fog collectors are:

a. Fog collector components costs (this includes the Raschel mesh, supporting poles and components for transporting and collecting water),
b. Maintenance and part replacements costs (this also includes the labor cost)
c. Other costs such initial research for finding the best place (considering topography and wind patterns) and deploying/testing standard fog collector at the site.
d. Fog collector lifespan (5-10 years, depending on the site wind speed and fog collectors design) (Qadir et al., 2018).

The cost of fog collectors are expressed in m2; currently the fog collectors costs between 25-50 USD/m2 (LeBoeuf et al., 2014, Fessehaye et al., 2017, Holmes et al., 2015 cited in Qadir et al., 2018), this means LFC with 40 m2 of mesh size cost between $1000 to $2000. It is worth mentioning that this cost is very site specific and depends on the mesh material and other equipment costs such as piping and water tanks.

There are many hidden costs involved in such projects example of such costs are the transportation and shipping cost, the cost of collecting data from standard fog collector, traveling cost to the site for construction or monitoring the progress and so forth. All of these mentioned factors are of course project and site specific and can be reduced by having a volunteers helping through the process (Klemm et al., 2012).

Considering the above factors the final cost of the collected water from different fog collectors around the world are presented in Table 10.

Type	Cost ($\$/m^3$)	Specific Information
LFC	16.6	No subsidy; distribution, storage and labor costs
LFC	5.7	No subsidy; distribution, storage and labor costs
LFC	2.5–3.0	Volunteer labor; production and distribution costs
LFC	2.5–3.0	Volunteer labor; production and distribution costs
Eiffel LFC	1.9	Production and maintenance costs.
LFC	1.4–1.6	Volunteer labor; production and distribution costs

Table 10. Final cost of m3 of water from fog collectors using LFC.

Table 10 indicates the cost ranging from 1,9 - 16,6 $/m3 or 0,002 - 0,016 $/L (Qadir et al., 2018), other studies also arrived at similar figures for example cost estimation based on Cereceda et al., 1992 for Chile fog collector is 1 USD/m2 or 0,01 USD/L.

II. <u>Dew collectors</u>

Parameters that decides the water cost of the dew collectors are the materials used and labour cost along with the lifespan of the foil (between 2-4 years (Besens et al., 2006) and the amount of water that is produced and stored.

For example, if only the foil of 30m2 is placed on the roof and fixed the cost of water produced is 0,044 USD/l but if the stand is built and additional isolation polystyrene foam is added to the system to increase the yield the cost of water increase to 0,34 USD/l (Beysens et al., 2006).

Equally the place of dew collector is also important, since it affects the material and labour cost of the project. But more importantly the total amount of water produced by the system is the key in bringing down the final cost.
As mentioned earlier dew collectors are very effective tools for collecting rain water but often the collected rain water is minused out of the calculation. A good example of such a scenario is the 850 m2 on-ground collectors in India, they collected 6500 liter of water in 2007 (minus the rain water) with cost figure of 0,074 USD/l but when the rain water was included in the calculation and adequate water tanks were added the expected output raised to 100,000 L which in turn brought down the cost to less than a cent 0.01 USD/l (Sharan et al., 2011)

Table 11 is summarizing the costs of liter of water produced by different dew collectors.

Project	Description	Ref.	Cost
India Kotahara	540 m2 off ground dew collector	Sharan et al., 2017	***0,001 USD/l***
India Panandhro	850 m2 of on ground condensor.	Sharan et al., 2011	*Without rain collection:* ***0,07 USD/l*** *With raing collection:* ***0,01 USD/l***
France Ajaccio island	3 m x 10 m of plane/off ground condensor	Beysens et al., 2006	***0,044 USD/l***

Table11. Dew collector water cost per liter.

Summary: Table 12 is summarizing the findings and cost per liter of water for each AWG system, the conclusion from the collected data is that the Dew collector and fog collectors are a cheaper way of producing water compared to active heat pump solutions. Although the figures are close between fog and dew collectors, the fact that dew collectors are easier to set-up and maintained along with better rain catching capability that can further bring down the cost further for the high end cost estimation of the dew collectors projects, when all considered it is clear that the dew collectors are the cheapest choice between mentioned methods of AWGs.

	Active-heat pump	Passive-Fog collector	Passive-Dew collector
Cost *USD/l*	0,02 - 0,04	0,002 - 0,016	0,001 - 0,044

Table 12. Dew collector water cost per liter. Detailed information about the origin of the numbers can be found in table 09 table 10 and table 11.

2.3 Conclusion

Through reviewing three different methods of collecting water from the atmosphere it is concluded that between all methods there are shared factors of air temperature, geological position and high relative humidity that should be met for any of the systems to work efficiently and in some cases such as dew and fog collectors to work at all.

Heat pump and active AWG solutions that use the Refrigerant Coolant or Peltier to bring a certain surface temperature lower than dew point to collect water from the atmosphere has a very high energy consumption (5.8 kW) and dependent on the availability of electricity on the site. They also require a very high initial investments but they use a well developed technology and if there is a problem an expert can be found to fix the device (although this is very relative to the location and country that the device is positioned). Despite the fact that the initial investment cost of the device is high, the final cost of water produced from the system is low due to the fact of high yield of the system per day (9-3000 l/day).

Passive fog collectors are devices that are dependent on availability and frequency of a fog in the site, their yield increase with larger size of mesh but the larger fog collectors tend to have lower life cycle since bigger surface area will have more resistance to the passing air and if a wind speed goes higher than 17 m/s it will destroy the mesh or the structure of the collectors.
When this happens in most cases the locals can not repair the collector and as a result the life cycle of it reduces from 5-10 years to 2-4 years, this of course will also affect the final cost of the water produced from the device since the amount of years that the device produce water is an important factor in calculating the final collected water cost.

Fog collectors have a yield of 3-12 m2 per day, but this number depends on the geological position of the collector and how much attention was given at the start of the project for selecting the right size considering the type of fog and dominant wind direction.

Fog collectors have been at the centre of attention since 1957 where the first study was done in Chile, since then lots of data and examples of different types of designs are gathered and are available, and the availability of such data make the process of improving the existing fog collectors design easier.
The main problem with such devices is the occurrence of high wind speed or wind storm that results in destroying the mesh or the structure. There are already solutions such as CloudFisher 3D mesh design or Multi-modular Funnel fog collectors that considered high wind situations & designed their collectors accordingly with downside of increasing the initial investment costs.

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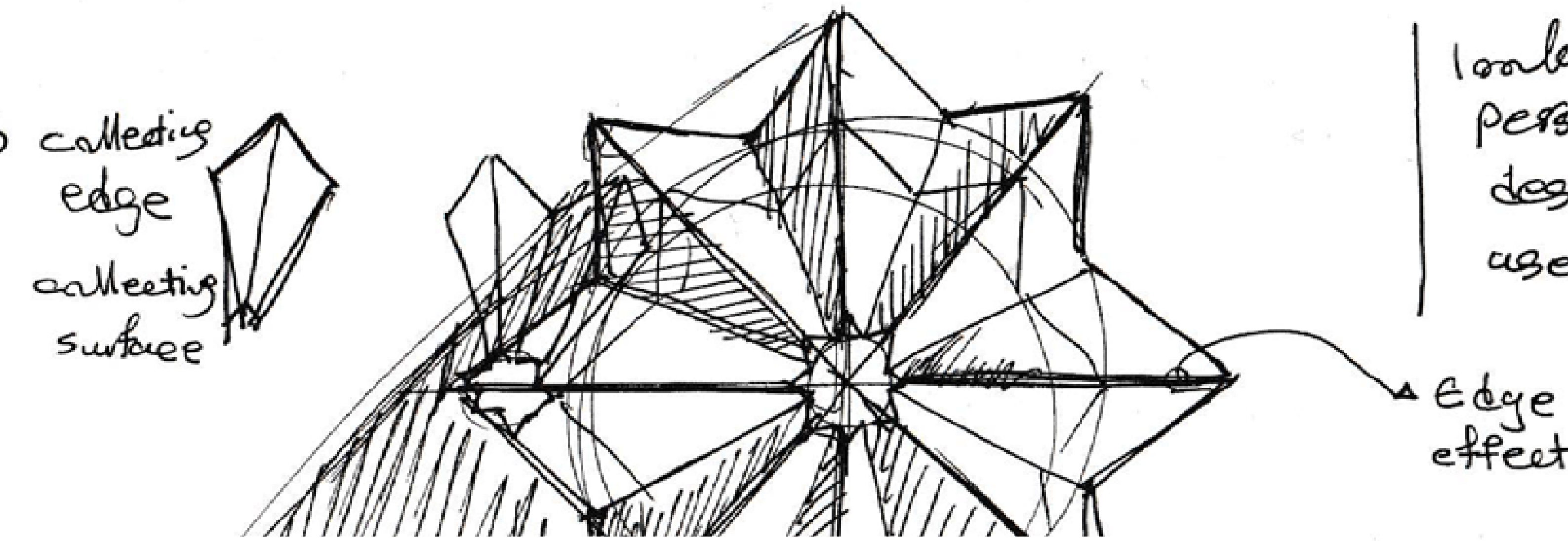
Dew collectors have generally very limited yields or water collection rates of 0,05-0,6 l/m2 per night, theoretically the yield can not exceed 0.8 l/m2 this is due to the fact that the amount of cooling energy that can be transferred between the dew collector material and atmosphere will not exceed 100 W/m2 (Sharan et al., 2017; Beysen et al., 2013). But what is considered as a drawback for dew collectors i.e. low yield of the system, can be improved by designing better collectors and cover more areas to increase the heat transfer capability and improving the dew and water collection from the surface and paying attention to the site and parameters that are required for optimum dew making and collection process (e.g. wind speed and it’s relative speed, the position of the device in accordance to the sunrise and sunset, clear sky, temperature and humidity)

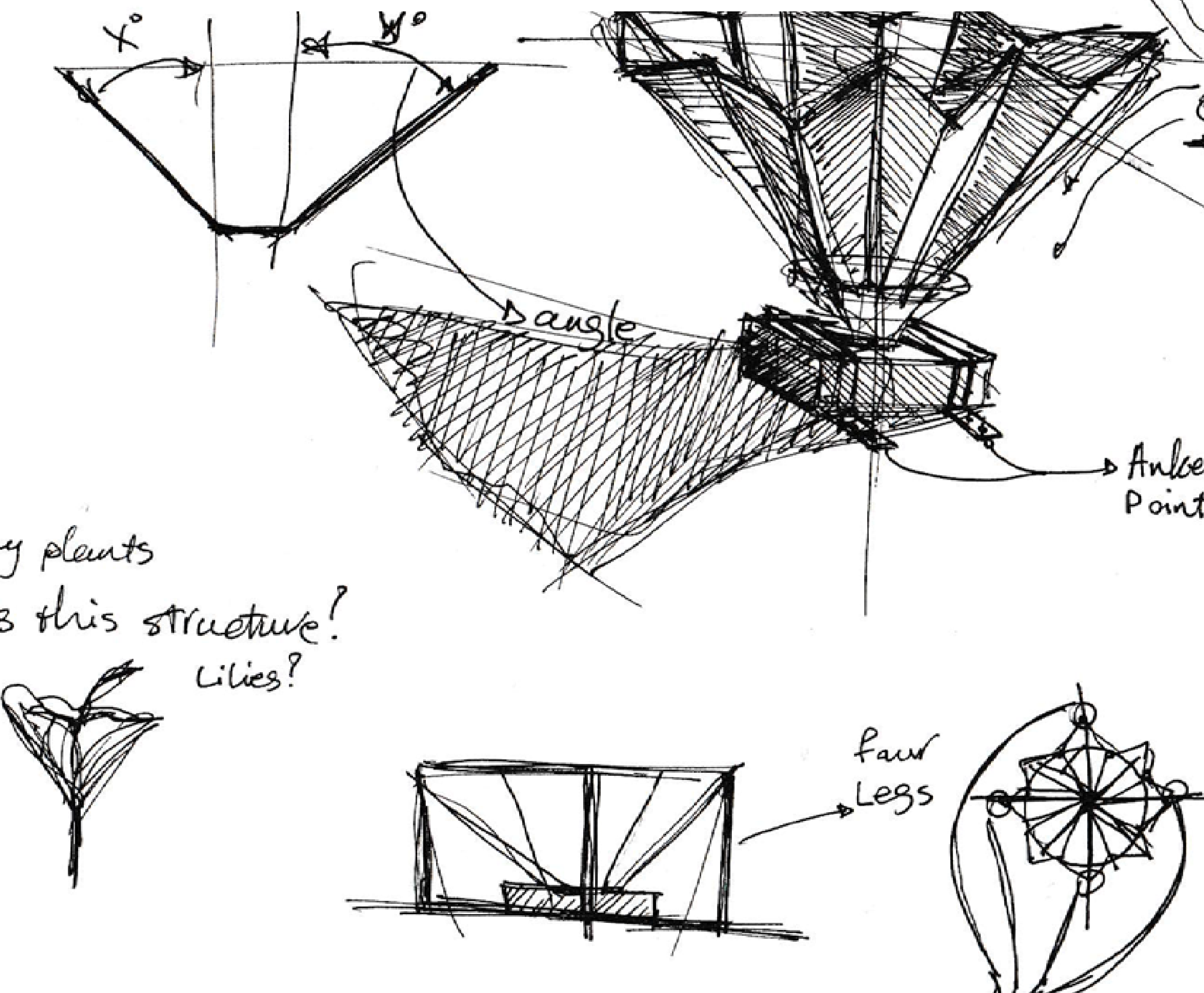
One positive aspect of the passive radiative cooling system or dew collectors, they can provide the cheapest and easiest method of collecting water in remote locations, since their main component is a PE foil that can be transported easily to the site and maintained or even changed by locals.

The only method that has much room to improve drastically is the Dew collectors, they are often neglected due to their low yield but their low cost and maintenance make them a perfect candidate for further research and enhancement, since improving the collection rate by refining the design will further reduce the cost and can compensate relatively low yield of the system when compared to other methods such as fog and active AWGs. For this reason, the aim of the next chapter will be improving the dew collector design based on the design parameters that are gathered through the literature review, biomimicry and examples from nature.



03. Designing

In this section a selected AWG method (Dew collector) is studied in further details to gather a design parameters and design a new improved version. Toward the end of the section few concepts are prototyped and tested.



3. Designing a new Dew collector

Passive radiative collectors and more specifically the dew collectors are the only devices between Fog and Active collectors that has more room to improve, this is mainly due to the fact that they have been ignored because of their low yield but on the other hand they have a very low cost of installation and easy to maintain which make this type of collectors very convenient for places that are remote and needs to be monitored and maintained by the locals.

With improving the design and the yield of the dew collectors it will have the potential to compete and be deployed to remote areas and have a positive effect on the specific site. The purpose of this study is to provide water for the arid to semi-arid areas that went under negative changes due to climate change and thus affected the ecosystem drastically, the collected water will be used for animals and rehabilitation of the soil and is not intended for human usage.

3.1 Dew collectors types & selected type for further investigation

There are three types of dew collectors currently in use:

I. On-ground, which consist of PETB foil in a ditch with 30 degrees angle on the sides.
II. Off-ground or alternatively called planar condensers is a 30 degrees tilted the plane of PETB foil placed on a frame with some ground clearances and styrofoam at the back for adding insulation from ground heat flux.
III. On-roof, this type of condenser is a foil on top of the roof or existing roof painted with hydrophobic paint, there are cases that further insulation e.g. styrofoam is added under the foil for enhancing the water yield. In all the mentioned methods there is a system (normally a PVC pipes) for transporting the collected water to a reservoir tank.

Desirable places for deploying the future dew collectors are in national parks or remote places in nature that are affected by drought, these sites do not have any infrastructure or building for placing the foil on-roof and also the on-ground solutions are prone to many problems such as contamination of collected water and damaging the foil while installing it, therefore the type that is selected for further investigation and improvement is off-ground version.

3.2 Design parameters

Based on the literature review following design parameters has been selected and presented in fig 17 for designing a Dew collector

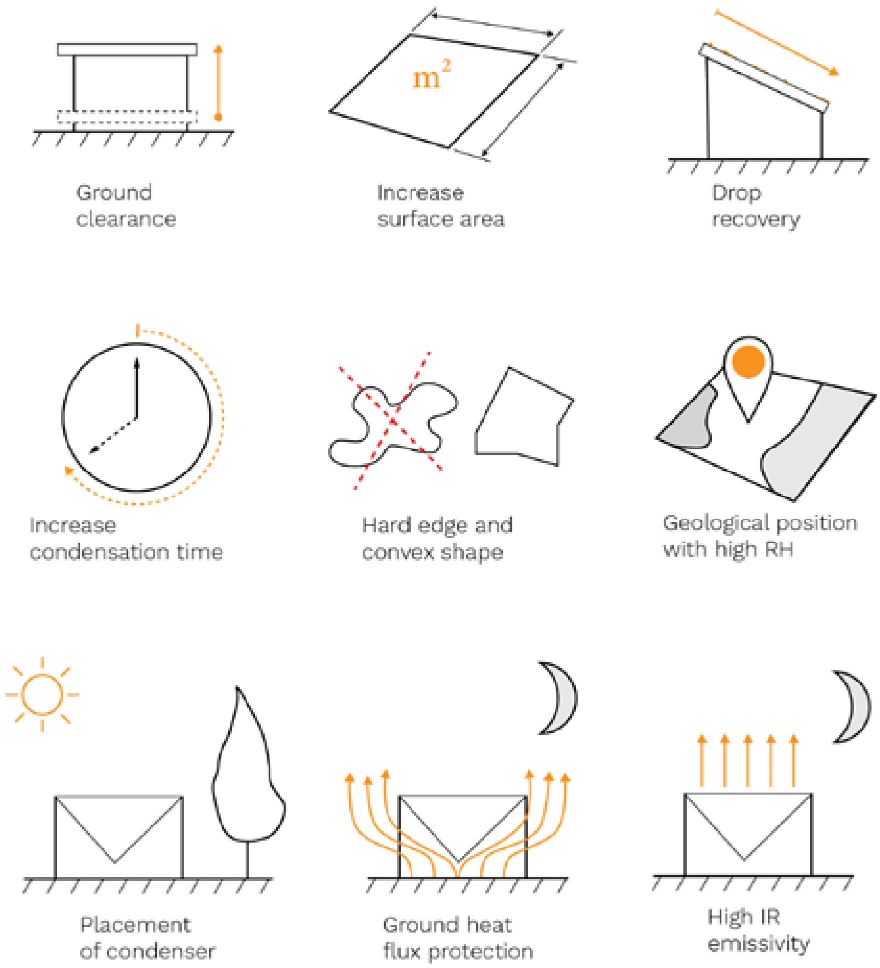


Fig 17. Off-ground dew collector design parameters.

Detailed explanation of dew collector design parameters are as follows:

I. <u>Increasing the condensation time:</u> the process of water condensation is dependent on many factors, one factor is the temperature difference between the surface and the surrounding atmosphere. Depending on the RH of the air temperature difference between the condenser surface and atmosphere should be similar or in other case 1-4 degrees less. Due to this reason the condensation window is limited to hours at midnight to early morning. By increasing the time of condensation the yield will increase.
For example, one way of doing this is to place the condenser facing North or West so that the early morning sunlight doesn't heat up the surface and the condenser has more time for condensing the water. (Sharan et al., 2011)

II. <u>Increasing the surface Area:</u> more area of collector will condense more water, due to low material cost this can be achieved by having more collectors or longer roll of film on bigger surface area.
III. <u>Shape and geometry:</u> paying attention to the geometry of the condenser is very crucial in getting more water out of the humid air, from “nature and biomimetic collection methods” section it has been observed that most of collecting plants have a convex and symmetrical geometry rather than concave, it is also clear form both the nature and laboratory test (see fig 8 in Radiative cooling - geometry section) that geometris and surfaces with rough/sharp edges tends to condense and form more droplet in a faster rates compare to organic and smooth surfaces.
IV. <u>Wind protection:</u> the passive radiation process relies on natural thermal convection and the high wind speed interrupt this process, the ideal wind speed is 1 m/s (Beysens, 2016) and wind speed larger than 4.4 m/s will stop the condensation process since the heat exchange between the foil and atmospheric air happens too fast and prevents the water vapour phase change. Due to this reason it is important to have geometry that protects the structure from wind.
V. <u>Droplet recovery:</u> after the formation of droplets on the surface they will stay there until they either join together to form a bigger droplet or they themselves become bigger so that their size become critical for the surface they are staying on and start rolling toward the desired direction.
This process can be assisted with shape and surface properties, example of optimum collection system can be found in “nature and biomimetic collection methods” section in which the Dryopteris marginata and Opuntia microdasys were examined (Sharmal et al., 2018; Ju et al., 2012) ; they both are presenting a microstructure and grooves that has a gradient roughness which leads to collection and transportation of water droplet in most efficient way (see fig 28, 29).
VI. <u>High IR emissivity:</u> Every surface gets a thermal radiation during the day and during the night it will emit it back to the sky, for cooling the condenser surface steadily during the night it is crucial that the condenser surface emit more heat than the amount it is receiving from the atmosphere so that it can bring the temperature lower than the surrounding and closer to the dew point. The surfaces that has a high IR emissivity are ideal for this purpose.
VII. <u>Ground clearance:</u> from the beysens et al., 2003 research one of the parameters that helped the condensation process was placing the condenser 1m above the ground.
VIII. <u>Position and placement of the condenser:</u> Dew collectors are depending on the temperature and relative humidity for producing water (high temperature with high RH will have more water to condense) along with calm environment that is not windy (wind not greater than 4.4 m/s) other factors such as having a clear sky (not cloudy so the heat exchange process happens faster) are very important, for these reasons it is crucial to study the geological position and climate of the site before deploying it.
IX. <u>Insulation from ground heat:</u> during the night the ground also emits thermal radiation if the dew collector is not insulated the heat will be transferred and absorbed by the foil, to prevent this the back side of the condenser is isolated with isolation material such as styrofoam.

3.3 Concepting & designing new collector

Three versions of off-ground dew condensers are currently in use (Fig 18) planar condenser Fig 18 (a), is the most common and standard type of condenser with 30° incline angle and additional insulation layer at the back, other types that are based on literature review are funnel shape and origami condensers (fig 18 b,c).
Funnel and Origami systems has higher yields compared to the planar version, Funnel shape has advantages of wind protection and Origami shape has advantages of having more sharp edges that helps the condensation process and total yields of the system. (Beysens et al., 2003, Clus et al., 2009)

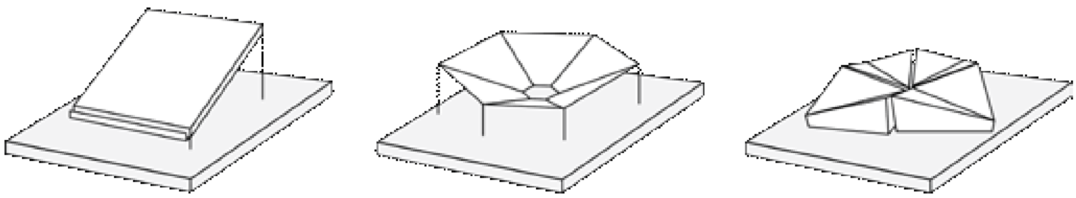


Fig 18. Off-ground dew collector types.

From the yield differences between funnel 30% (Beysens et al., 2013) increase and origami with two times more efficient (Nilsson, 1996) than planar version, it is clear that both shapes of funnel and origami are more efficient than planar version. Fig 19 is studying the effects that leads to such improvements.

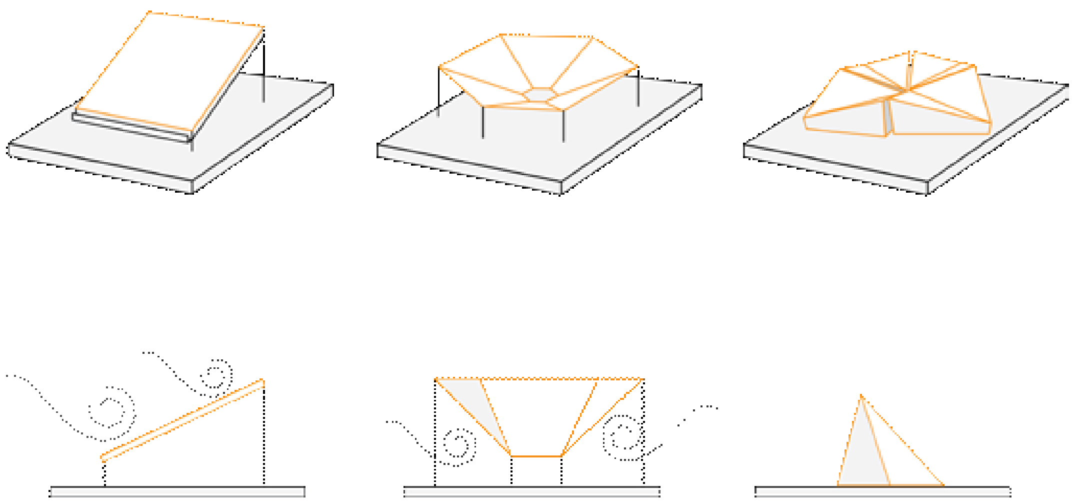


Fig 19. Off-ground dew collectors form and their effects on the condensation. Planner: wind affecting the condensation due to open surfaces. Funnel: advantage of wind protection. Origami: having sharp edges that assists the condensation.

Planar version has open surfaces that wind directly can cool it down, while the funnel shape has certain protection against it and incase of origami shape, it has more sharp edges that help the condensation process.

From these findings, the focus shifted toward the funnel and origami shape and how to combine these two shapes to improve the overall yields. Following concepts are presenting the designing and thinking process of achieving this goal.

3.3.1 Concept #1

Following concepts are results of combining two methods (funnel and origami) of condensing dew water .

1. **<u>Cone concept</u>**
   Cone shape concept is a basic form of funnel shape without any sharp edges, the angle is set to 30° (60° cone angle). This number is based on testing results of various angles and effect of wind on the structure in Clus et al., 2009 study (refer to 2.1.2 - Geometry section under Passive AWG).

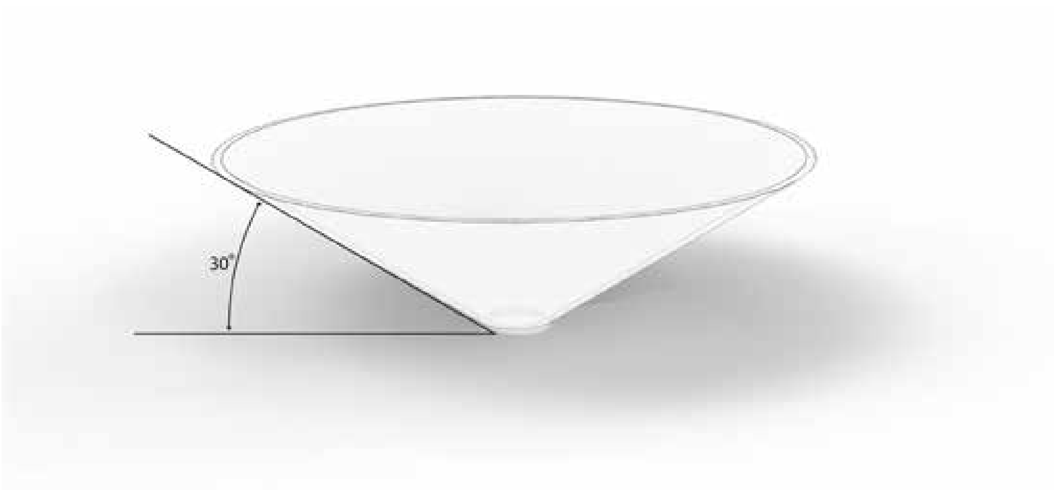
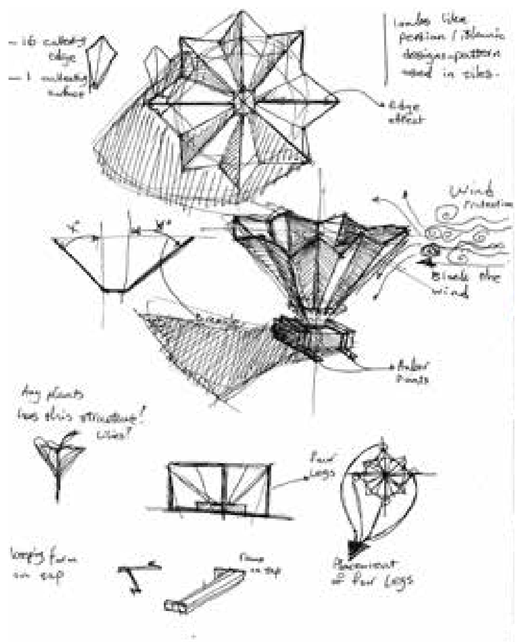


Fig 20. Cone concept.

Cone shape is a reference shape for comparing the condensing and collectivity capability of the funnel shape when the surface area is increased and sharp edges are added to the structure in the following two concepts.

2. **<u>Polygon- 6 sided</u>**
   The transition of conical shape to polygon shape can be done in many ways, some of these ways are presented in fig 21, in which the initial concepts are presented.



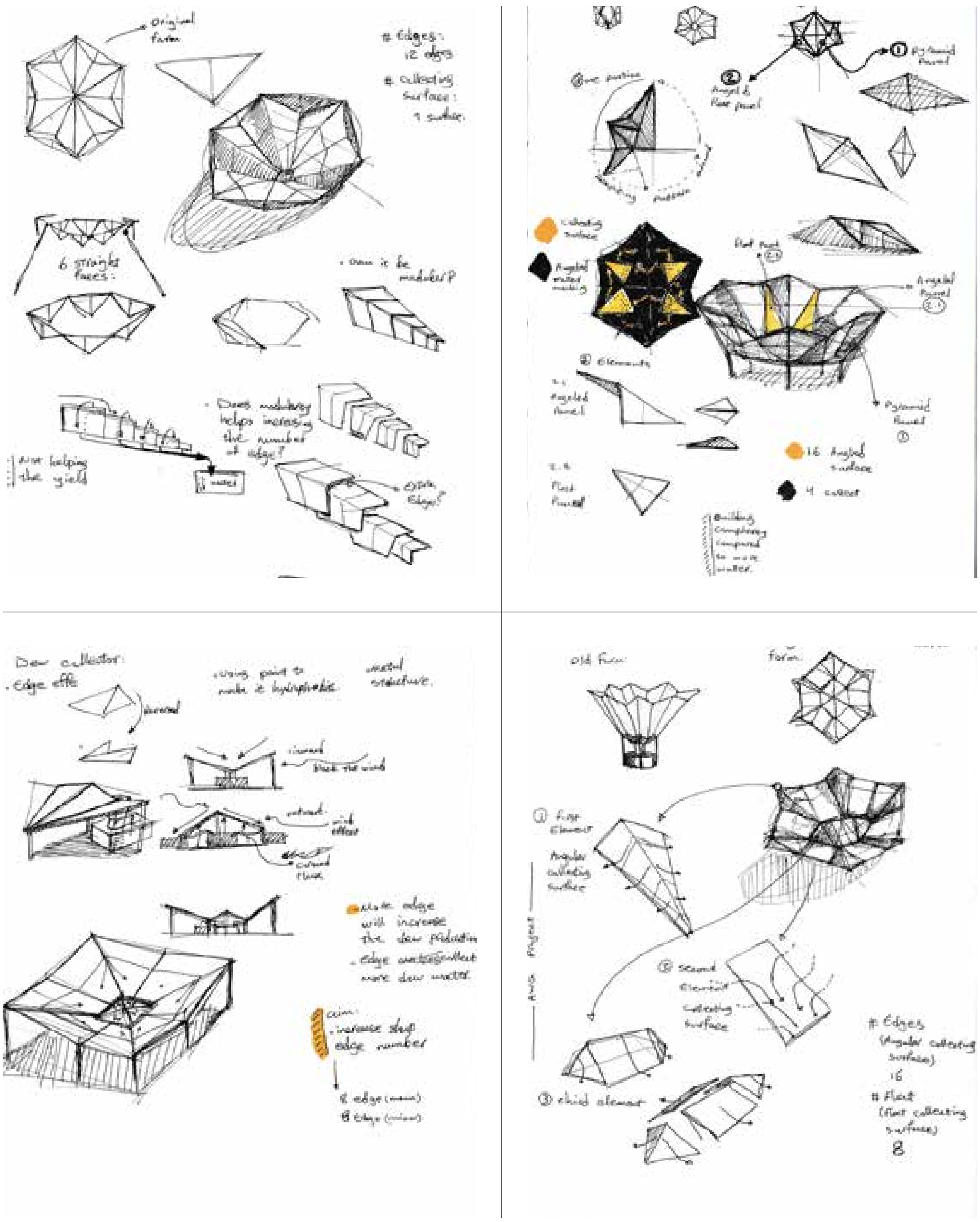


Fig 21. 6 sided polygon initial concepting and sketches.

At the end of concepting the simple 6 sided polygon with sharp edges at the bottom of the cone and more flat at the top was chosen, this is mainly to keep the structure simple and avoid additional panels at top such as in fig 46 b for wind protection.

The final concept has two 6-sided polygons (Fig22), one bigger diameter polygon at the top and smaller version at the base, following the 30° line from the top to the bottom. Other reasons for selecting the polygon shape is that it has edges that can be continued and altered (i.e. with change of height) to make sharp edges to mimic the Origami concept from Beysens research.

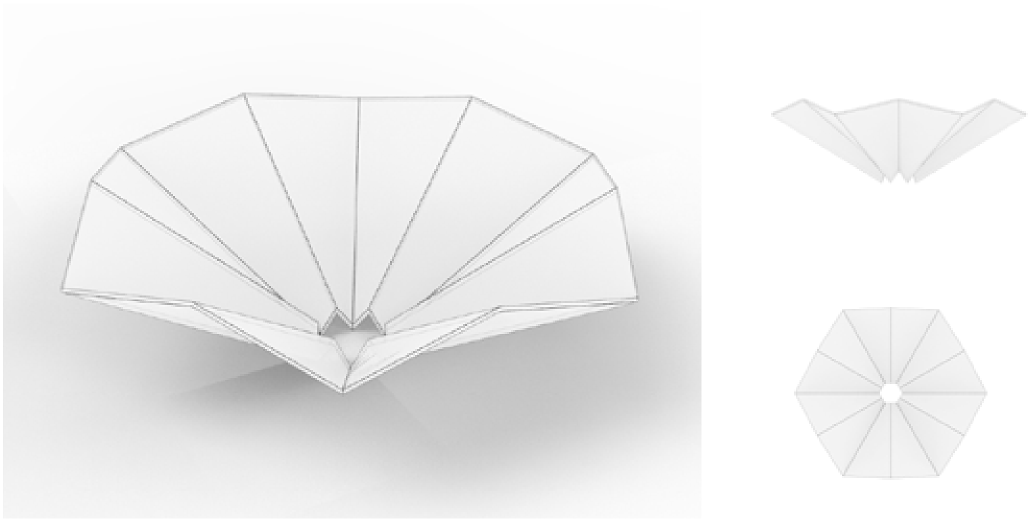


Fig 22. 6 sided polygon concept.

Here the edges and their relative angles becomes sharper when they get closer to the base, this is helpful since the heavier cold air sits at the bottom of the cone due to buoyancy and more water condensation takes place around that area, since the water condense more around sharp edge the overall yield of the system should be increased.

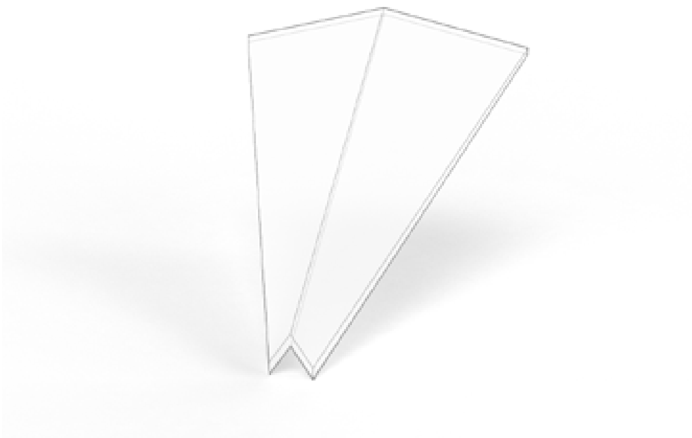


Fig 23. Edge angles differences at top and bottom

3. **Polygon - 8 sided**
   To study the effect of edges on dew condensation number edges is increased to 8. Here the same principle of 30° line is applied with the main difference of increasing the surface area and edges.

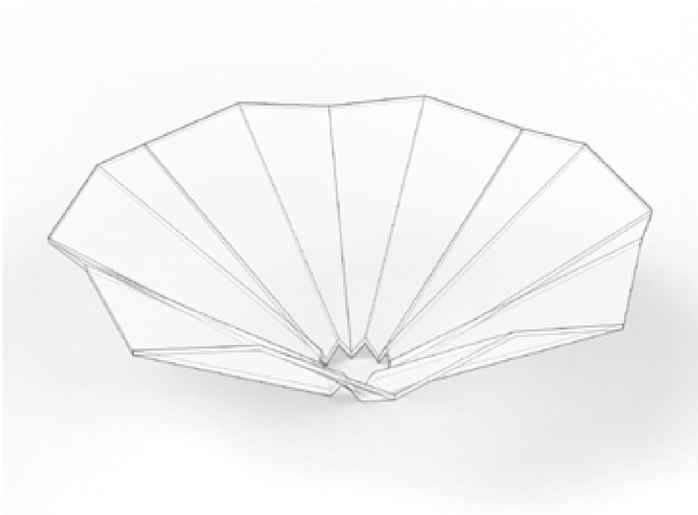


Fig 24. 8 sided polygon concept.

3.3.2 Concept #2

Following concepts are based on the reviews and inspiration from nature and other methods of producing water from the atmosphere, the basic form of the collectors are based on the concept #1 and additional pattern, parts and materials are added to further enhance the water production.

1. **Cactus spike**
   Based on Ju et al., 2012 Research and findings, cactus spine form and surface properties assists water collection from fog. Detailed explanation of spike properties can be found in Water collecting and repelling methods in Plants under 2.1.3 Nature and biomimetic collection methods section.

   But in summary the conical geometry of the spike produce laplace pressure gradient, this is due to radius differences in the conical shaped spine where the driving force will push the water droplet from smaller diameter where the pressure is higher (the tip) to the larger diameter where there is less pressure (base of the spine) this is illustrated in Fig 25.

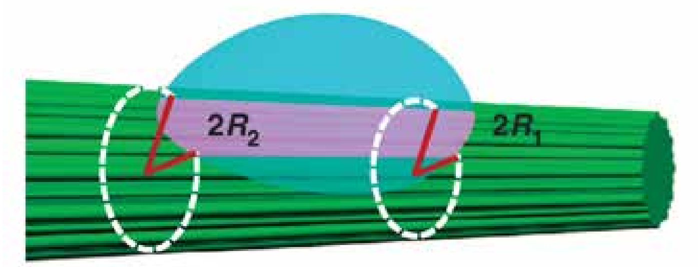


Fig 25. Driving force behind the water movement due to radius difference in the geometry. (Ju et al., 2012)

Using this information sets of conical spikes are placed at the edge and planes closer to the base. The placement of the spikes as explained in fig 26 is due to having a cooler air at the bottom of the structure (due to buoyancy) , hence more condensation happens at that area.

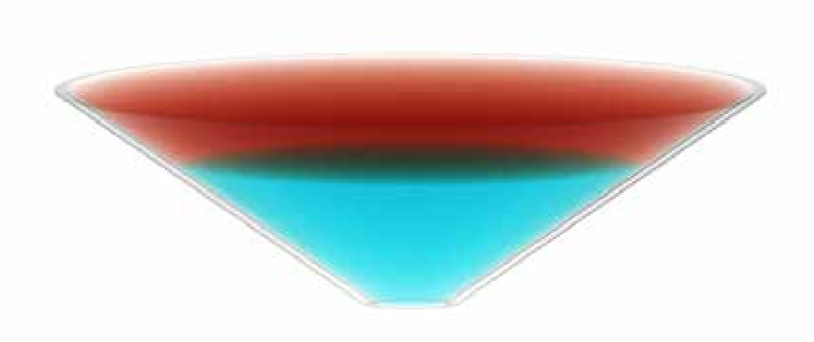


Fig 26. Due to the shape, the cooler air is sitting at the bottom of the structure and warm air at the top.

Putting everything together the resulting shape of one side and the whole structure is presented in fig 27.

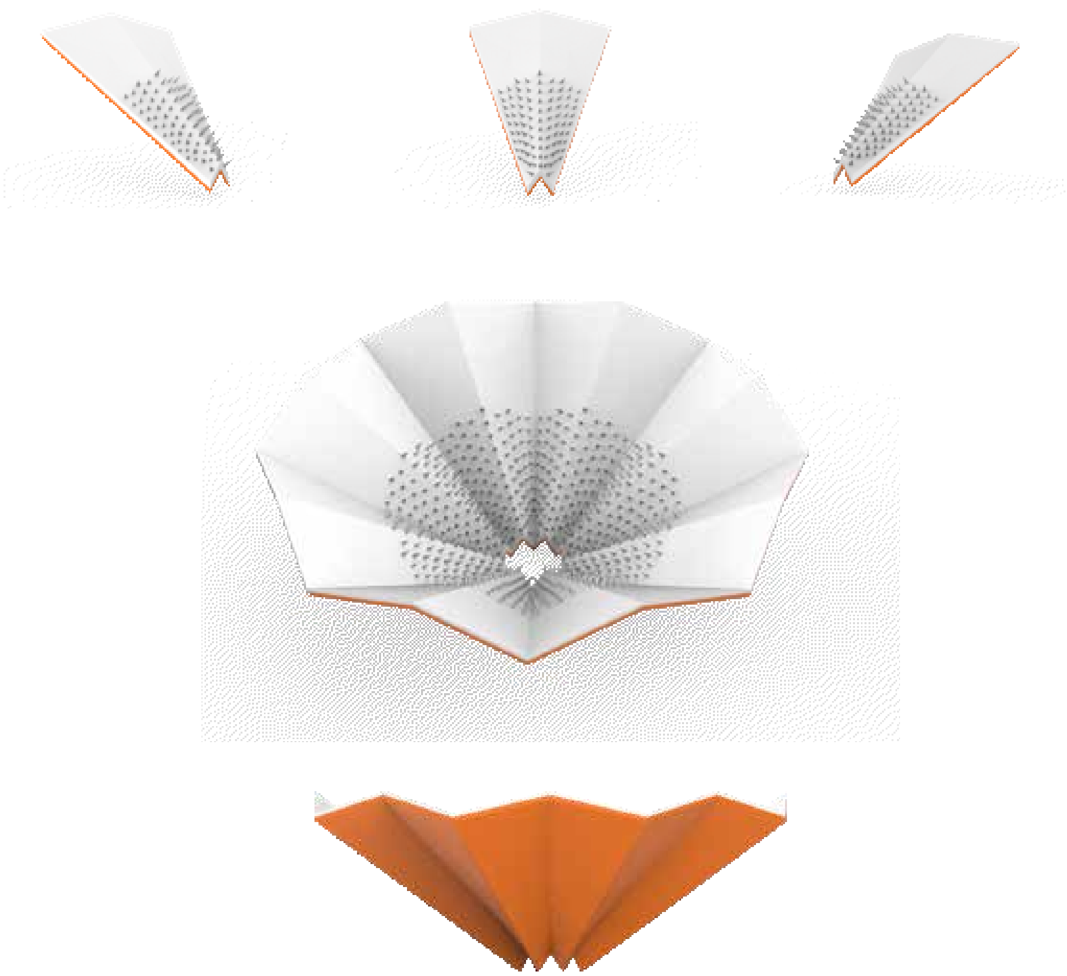


Fig 27. 8 sided polygon with cactus spikes concept.

2. **<u>Copper pipe</u>**
   Copper pipe can be also used for collecting dew, a study from Seo et al., 2016 experiment this by putting copper pipe with different surface coating and properties to the test, the result was that bare copper with no coating does best in collecting water (full explanation can be found in 2.1.4 Other methods).

   Here the copper pipe is used for assisting the water flow (Fig 28) by having them placed in on top of the film with sharper angle.

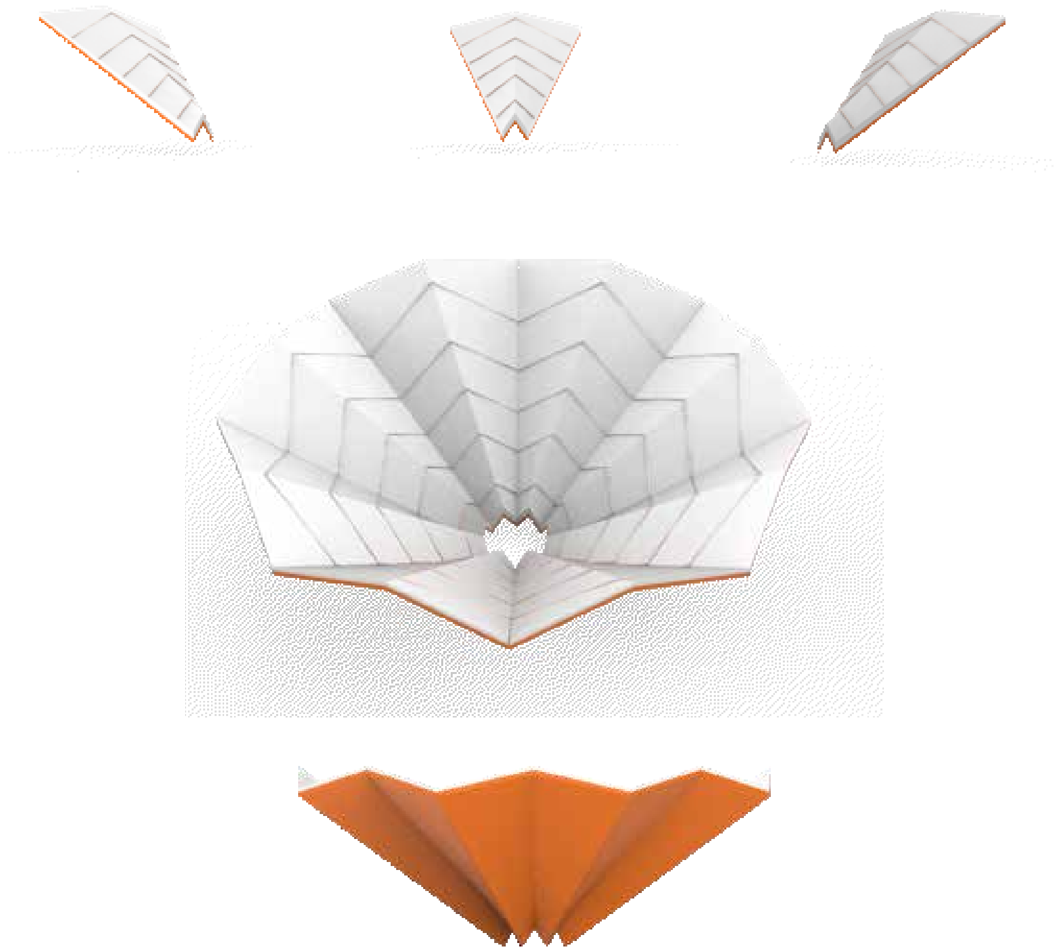


Fig 28. 8 sided polygon with copper pipe for assisting the water flow.

In other concept the copper pipe is used as an additional material and surface for condensing water (fig 29).

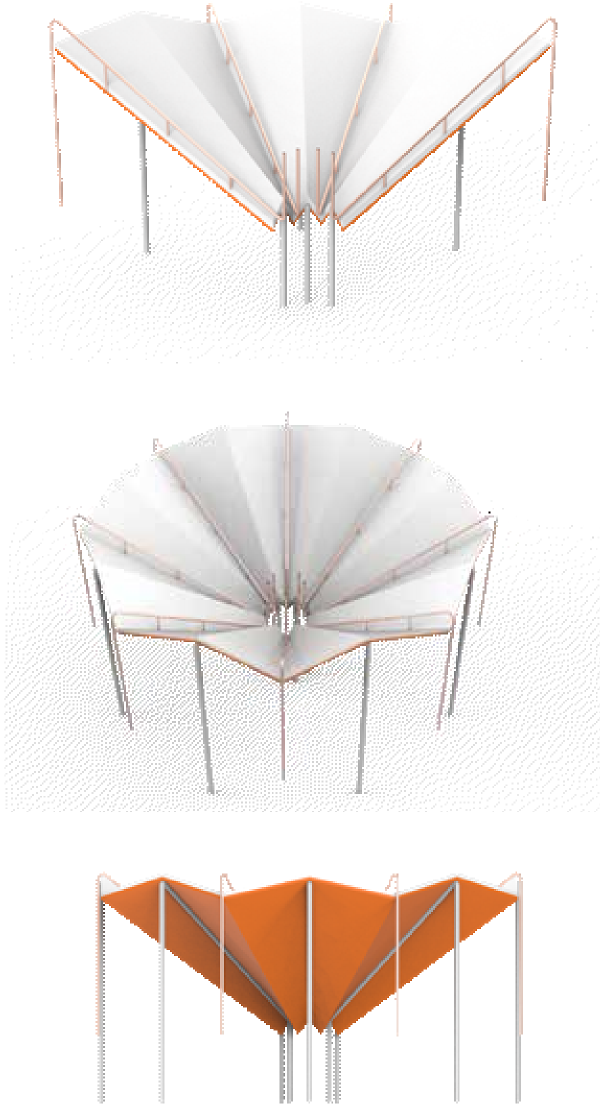


Fig 29. 8 sided polygon with copper pipe for increasing the water condensation.

In the second concept pipes are placed in an area that mainly collect the water (valleys section in polygon), they also circulate the air inside them and further assist the condensation. The circulation happens due to the temperature difference at the base and top of the structure.

The design of the condenser can be improved even more with more concepting but the further designing is put to pause for testing the existing hypothesis. This includes testing the effect of funnel shape and the effect of having more edges on the structure along with using a copper pipe for improving the yield. In the next section the testing process and the results are presented.

3.4 Testing & results

To put the concepts and hypothesis of edges and their effects on collecting water a chamber with dimensions of 23x23x23cm has been made and sets of concepts (Cone, 6-sided polygon, 8-sided polygon and Copper) has been put to the test.

3.4.1 Setup & chamber design

Fig 30 is presenting a chamber where the humidity is raised to 90% and the process of water condensation on the 3D printed concept is observed and documented.

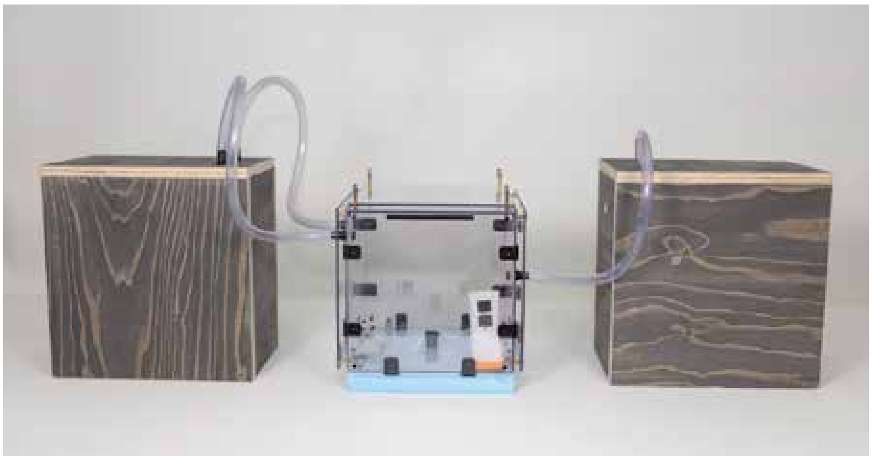


Fig 30. Condensation chamber setup. With the chamber in the middle, the humidifier on the right and a suction system in the left.

Chamber is made out of acrylic sheets with additional layer of insulation foam at the bottom for preventing heat exchange between inside and outside air. Humid is produced by BU1300W-I Bionaire ultrasonic humidifier and passed to the chamber, the temperature and RH of the chamber is measured and documented by Telldus sensor.

The aim of the test is to determine the form and its effectiveness on droplet recovery. Since a big part of improving the dew condenser is to improve the droplet collection and preparing the surface for the next round of droplets.

Other factors such as IR emissivity and wind protection need to be tested in other methods e.g. 1.1 scale model of the condenser in a specific test site.

The test starts by the humidifier pushing humid air inside the chamber and the humidity increases over time, from testing at temperature of 20-23 °C humidity reach 90% in 45 minutes, each model is left in the chamber for ~1 hour and the collected water and droplet formation and possible formation of water stream is documented after this period.

3.4.2 Materials

From concepting section, four concepts has been selected, 3D modeled in Fusion 360 and 3D printed with PLA material. Since PLA is not water repellent (author noticed after testing the model in the chamber) a layer of waterproof PE fabric was added to the model but due to high humidity in the chamber even the PE fabric started to absorb the water.

Final solution was to use polycarbonate film with a thickness of 0,5 mm. Each piece was cut and heated to match the structure form of the specific concept. Fig 55 is presenting the process of improving the cone concept shape coating.

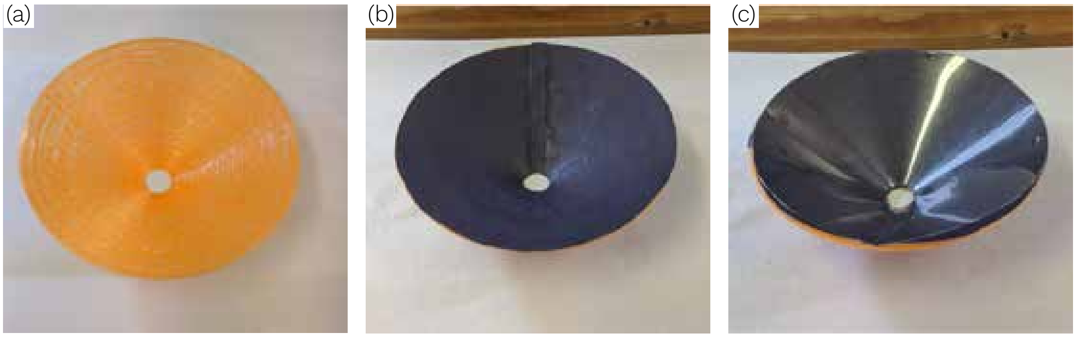


Fig 31. (a) PLA base (b) with PE fabric (c) Polycarbonate film on top of PLA and PE fabric.

3.4.3 Testing

Four concepts were selected from Design and concepting section, these concepts were selected due to the following reasons:

i. Cone, 6-sided and 8-sided polygon (Fig 32) were selected to study and compare the effects of having no edge and multiple edges on the droplet recovery and overall yield of the system.

Fig 32. From top to bottom, cone concept, 6 sided polygon and 8 sided polygon

ii. Copper and cactus spike concepts (Fig 33); these two concepts can not be fully tested with current testing method and scale of the models, but nevertheless findings were interesting for copper concepts.

Fig 33. From top to bottom, Copper concept and cactus spike concept.

3.4.4 Testing Results

1. **<u>Cone concept</u>**

   Fig 34 (a) is presenting the cone concept before and Fig 34 (b) after testing in the chamber. The results indicate that water droplets are becoming fixed to the surface (Fig 34 c) and not many water streams are formed, as a result of this form properties, the yield of the system is very low (Fig 34 d)

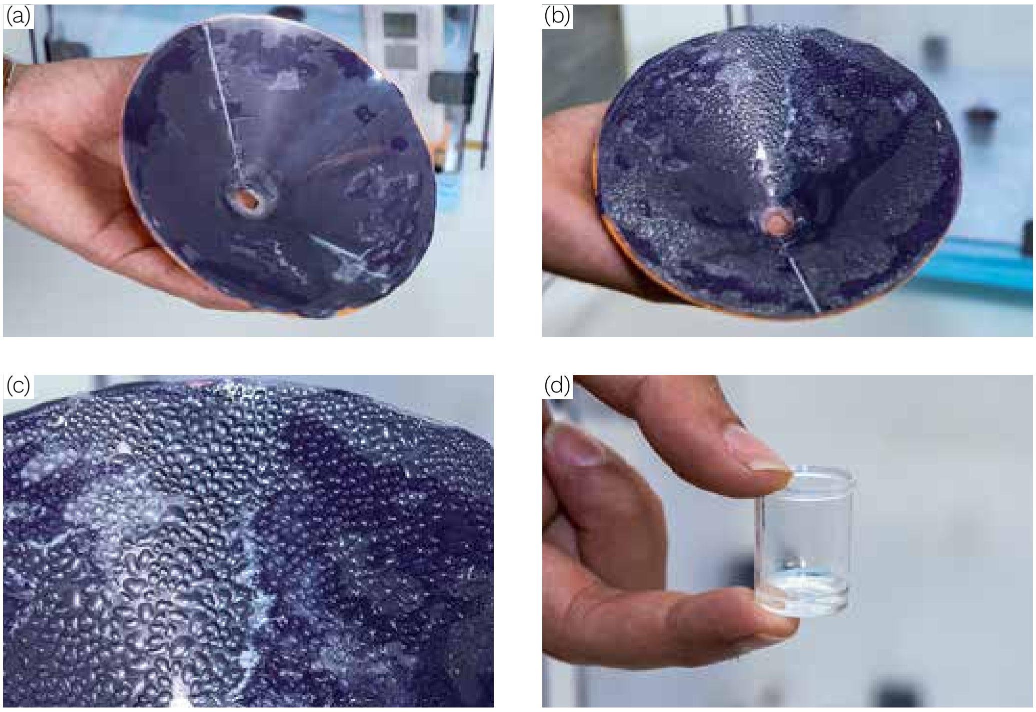
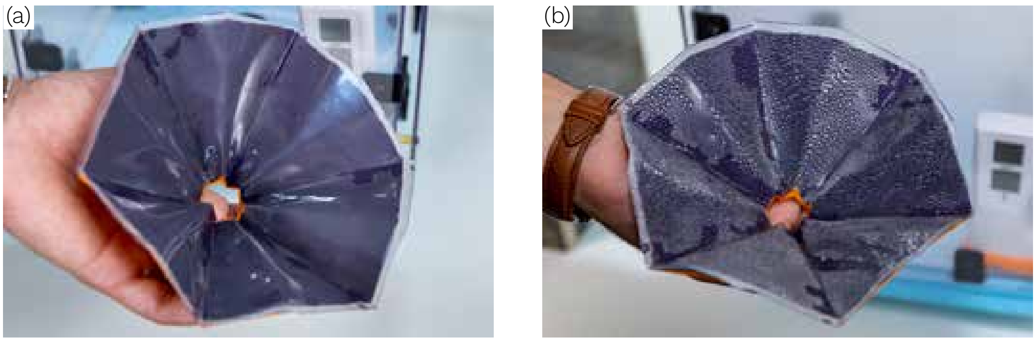


Fig 34. Testing Cone concept (a) cone concept before putting in the chamber (b) after the chamber (c) droplet fixed on the surface (d) system yield

2. **<u>6-Sided polygon</u>**

   Here it has been observed that the droplets start to form on the edges (fig 35 c) and form water stream (Fig 35 d,e) and drop to collecting area at the bottom of the polygon.



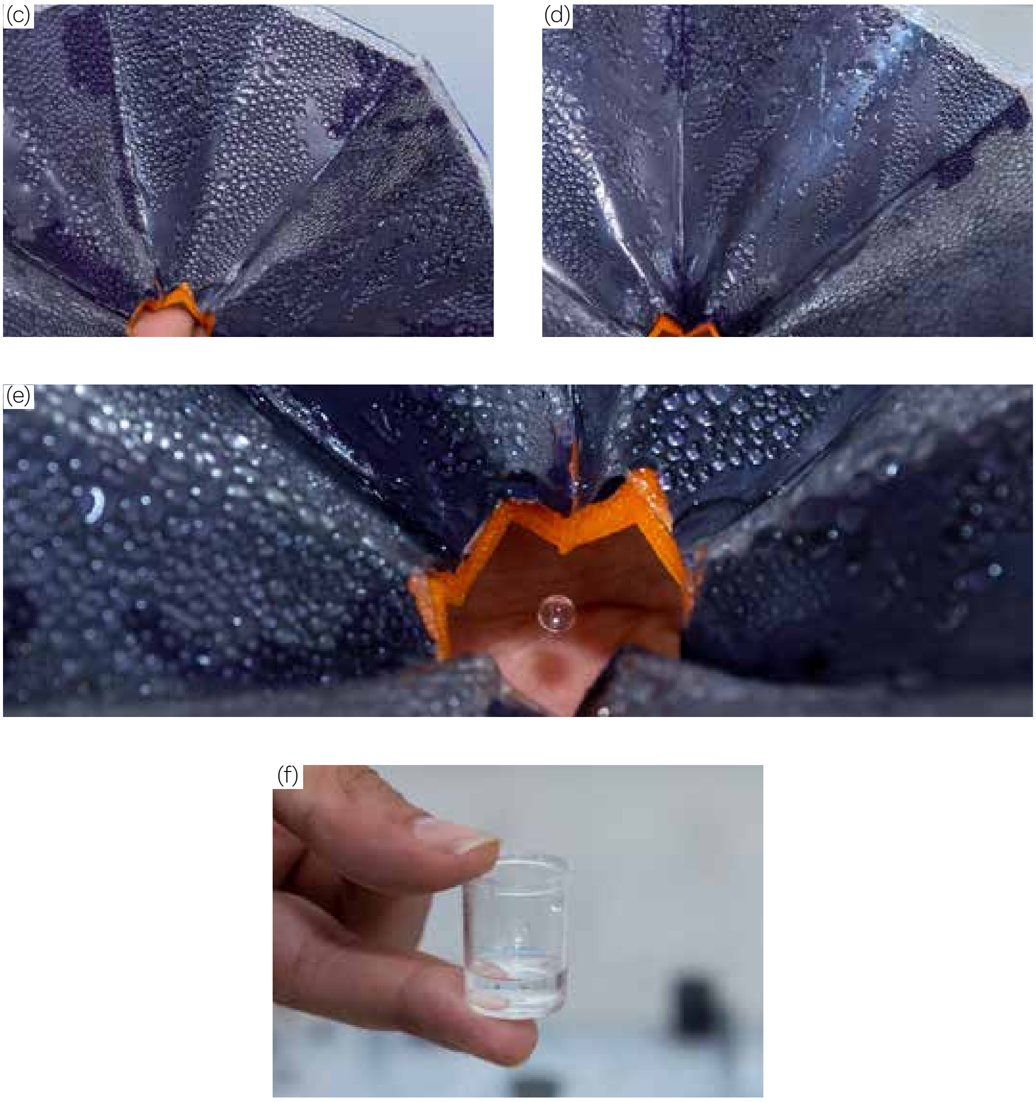


Fig 35. Testing 6-sided polygon concept (a) 6-sided polygon concept before putting in the chamber (b) after the chamber (c) droplet forming on edges (d) droplets forming water stream (e) water dropping into the collecting area (f) total yield

It is also clear that the droplets become stationary on flat surfaces where there is no sharp edges of the structure, these areas are mainly around the top of the polygon.

3. **<u>8-Sided polygon</u>**

This concept has the most edges compared to other concepts. After testing in the chamber the results indicate that the water droplets form on top of the edges (Fig 36 c) and drop down and collect the rest of the droplets while forming a stream toward the collecting area in the centre (Fig 36 d).

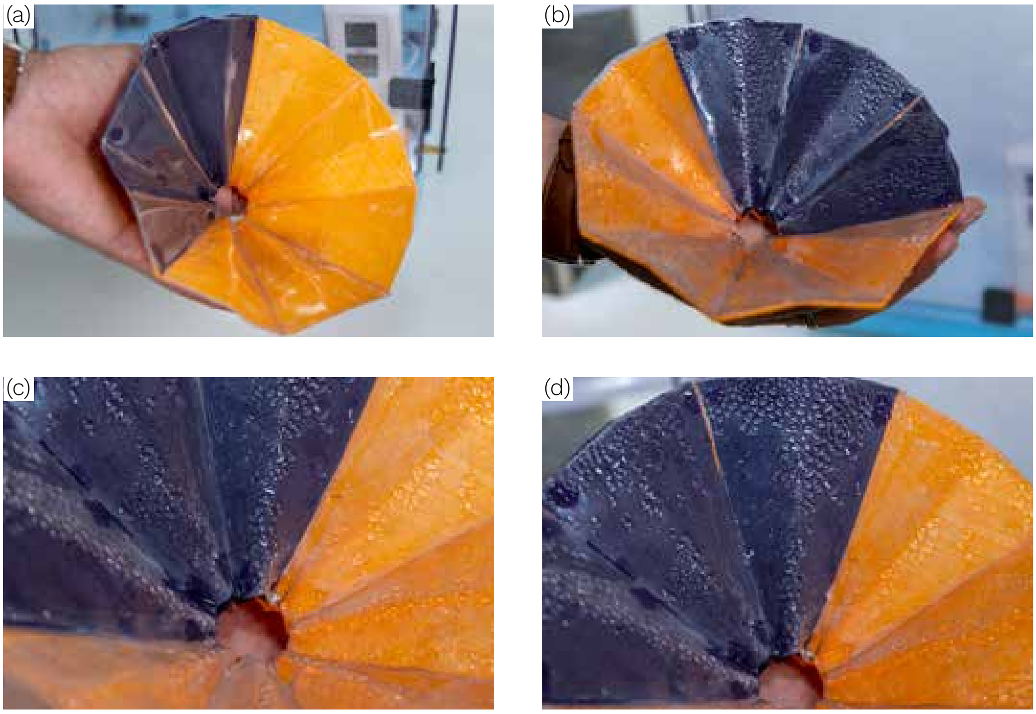


Fig 36. Testing 8-sided polygon concept (a) 8-sided polygon concept before putting in the chamber (b) after the chamber (c) droplet forming on edges (d) droplets forming water stream

This concept collected most water compared to other concepts (Fig 37).

Fig 37. 8-sided polygon concept collected water.

4. **Copper pipe**

This concept was mainly tested in the chamber to study the water formation on copper line. Based on the results, the water forms on top and after its size become critical it drops on the surface underneath it. (Fig 38)

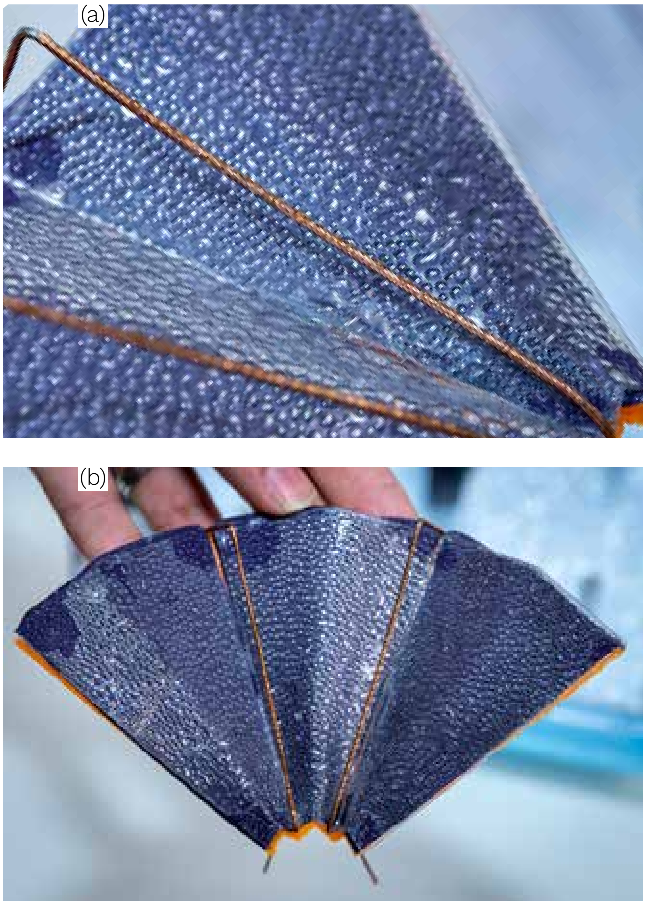


Fig 38. Copper pipe concept, collecting water on the copper line

Other interesting findings was the way the water formed on 3 sides of the polygon (Fig 39) and reduction in number of water streams; this effect could be explained by not having the cool air stuck in the funnel shape at the bottom of the structure, since the structure is now open (compared to 8 sided polygon that is completely closed) the air free to move and the cooler air won't get stuck around the bottom of the structure.

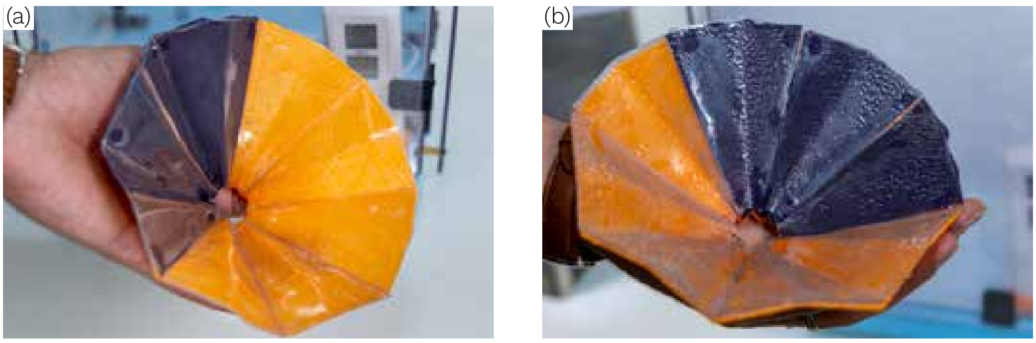


Fig 39. Testing copper line concept (a) copper line concept before putting in the chamber (b) after the chamber

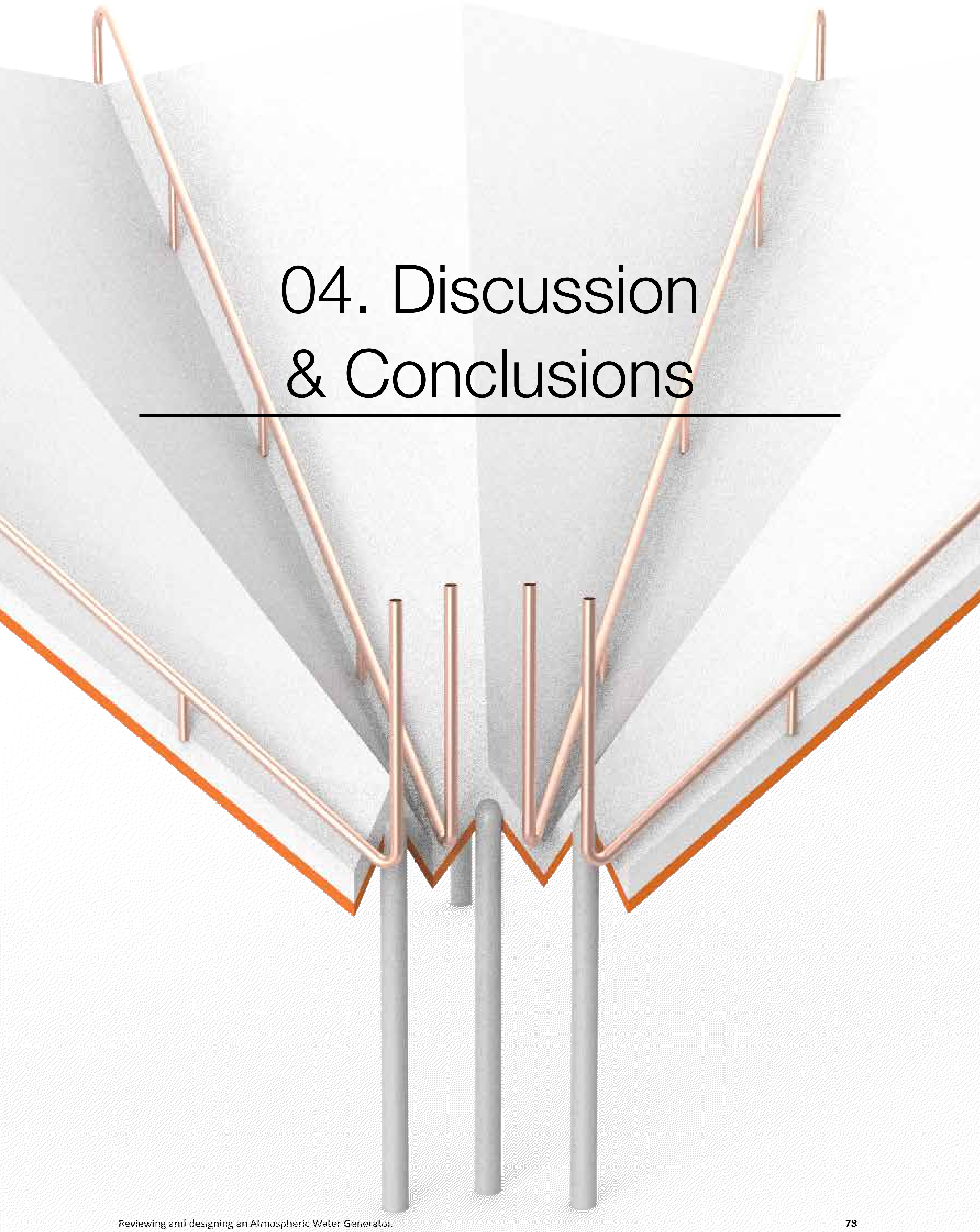
4. **Cactus spike**
   Since the model is scaled to fit in the chamber the size of the spikes are very small compared to the overall size of the structure. This made the process of putting polycarbonate sheet and forming the spike impossible, hence the testing of this concept was abandoned with current setup.

3.4.5 Results & summary of findings

The test results showed that the 8-sided polygon is most effective in droplet recovery and support the hypothesis and the importance of using sharp edges in funnel form. Droplets are formed around the edge and slide down while collecting other droplets forming a water stream and improve overall yield of the system while preparing the surface for the next round of droplets.

The effect of adding two more sides (from 6-sided to 8-sided polygon) increased the overall yield, therefore it can be concluded that further increase of sides will improve the yield due to increase of sharp edges and surface areas for water condensation.

Testing of copper line concept showed the importance of having a closed funnel shape on behaviour of droplet and water stream formation, when the shape is closed the cooler air will be at lower areas and assists the condensation process by bringing the surface temperature closer to dew point.



04. Discussion & Conclusions

Discussion

There are many studies available regarding both active and passive AWGs, from these data base it became clear that both fog and active collectors were the main focus in past decades for further improvements. On the other hand the passive radiative cooling methods / passive dew collectors are not developed as much as other mentioned methods.

Based on Beysen (origami, egg shaped and planner dew collector) and Clus (CFD study of passive dew collectors) research and other nature inspiration (e.g. cactus spike, Namib desert beetle elytra and bermuda grass) sets of concepts were made to combine different methods and findings in the field of passive dew collectors.

One major findings was effect of adding sharp edges to funnel shape; this idea is based on studying examples from nature (cactus spike (Ju et al., 2012) and Cynodon dactylon bermuda grass (Sharma et al., 2016) and behaviour and formation of water droplets around the edge (Medici et al., 2014).

Other ideas were based on combining active and passive methods (e.g. copper concepts) in which the air is circulated naturally around and inside the funnel shape without any additional energy input. This concept couldn't be tested since the chamber that was built had many limitations, such as the effect of ground heat flux and IR emissivity were not present in the chamber; the only test that could have been done was studying the water droplet formation and behaviour or effect of form on water droplet recovery.

Conclusion

AWGs are becoming a centre of research and interest for mitigating and countering climate change and droughts. Through this study, AWGs were reviewed, compared, designed and tested with the aim of improving the existing method of water collection from moist air.

In reviewing and selection process of AWGs, two types of active (heat pump, active AWVP) and passive collectors (fog and dew collectors) are reviewed and compared. The results indicate that the active systems have the highest yield (9-3000 l/day) and cost (0,02 - 0,04 USD/l), on the other hand, the lowest cost (0.001- 0,044 USD/l) and yield (0.05 - 0,6 l/m2) is associated with dew collectors.

Considering the aim of this thesis the collected water is meant for animals and rehabilitating the soil in remote areas that are affected by droughts due to mismanagement and climate change. Based on this aim, between the mentioned collectors, the dew collector is chosen for further improvement; this is due to the fact that this system has the lowest cost (both structure-wise and final water cost) and least complexity in terms of usage, transportation and installation. Using biomimicry (cactus spike, Namib desert beetle elytra and bermuda grass) and literature review (Funnel shape from Clus et al., 2009, and origami shape from Beysens et al., 2013) sets of concepts were made and tested to see the effects on droplet recovery and overall yield of the system.

The testing results showed that 8 sided polygon shape which has the most edges, collect the most water and has the best droplet recovery (droplets form faster on the edges and there are more water streams visible in the test results). These findings support the author's hypothesis of having a combination of a funnel shape and sharp edges will increase the overall yield of the system.

The design process of this work was a combination of collecting information from literature, nature and using this information to design a new concept and testing the hypothesis that the design was based on.

Since this work is a multidisciplinary topic it was crucial to follow and understand each discipline (i.e. design and engineering) process to find the optimum results. In engineering and it's related projects (e.g. active AWVPs and surface properties for repelling the water) often the project is very result oriented and the long term effect is not studied nor considered, in the same manner in design related topics the scientific facts (in this case thermodynamic rules) are ignored and the design is based on very limited information that affects the results of the project.

It was crucial for the author to understand and be aware of each methods advantages and limitations to be able to achieve a design that is based on design and engineering discipline and findings.

It has been always a challenge to find a fine balance between engineering and design field, throughout the research and literature review of this thesis the author noticed that information (even though they are published in well established channels) in media or academic papers are not always absolute. The example of this case is Zibold condenser that it was first thought that is condensing water from radiative cooling and many designs after 1912 (such as aerial well) well based on this idea but now the researchers (Nikolayev et al., 1996 cited in Beysens et al., 2006) proved that such structure could not work for dew condensation, due to the fact that the surface temperature of the stones in such a large structure could not possibly reach the dew point hence the condensation will never happen. They also speculate that the water that was gathered in Zibold condenser might have been the result of fog interception.

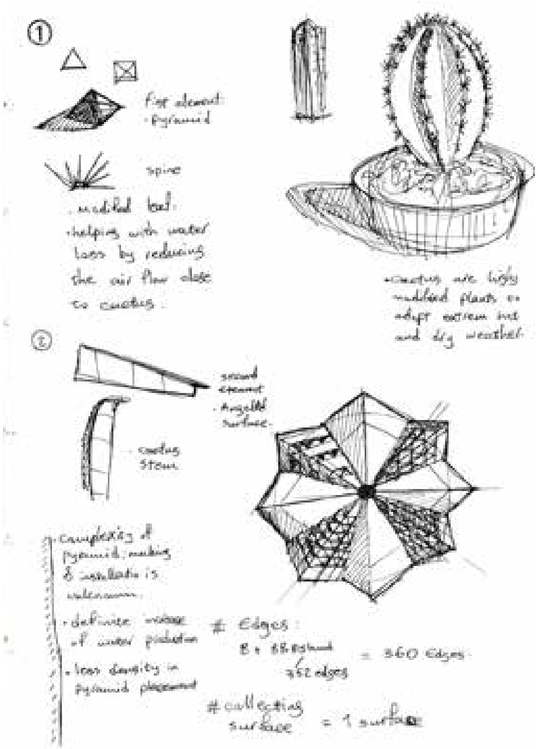
Or the example of beetles collecting water from fog that took over the media and was published in many channels, this study was based on Parker and Lawrence research (Parker & Lawrence, 2001) and it was concluded that hydrophilic peaks surrounded by hydrophobic ridges are the main reasons for collecting water from the fog, since the water from the fog is settled on the smooth surface of the bump and later after the droplets size become critical it starts rolling down towards the head. But such result and conclusion are now questioned since there are many other beetles that actively collect fog water in nature such as O. bicolor and O. unguicularis with completely smooth elytra surface and regular grooves.

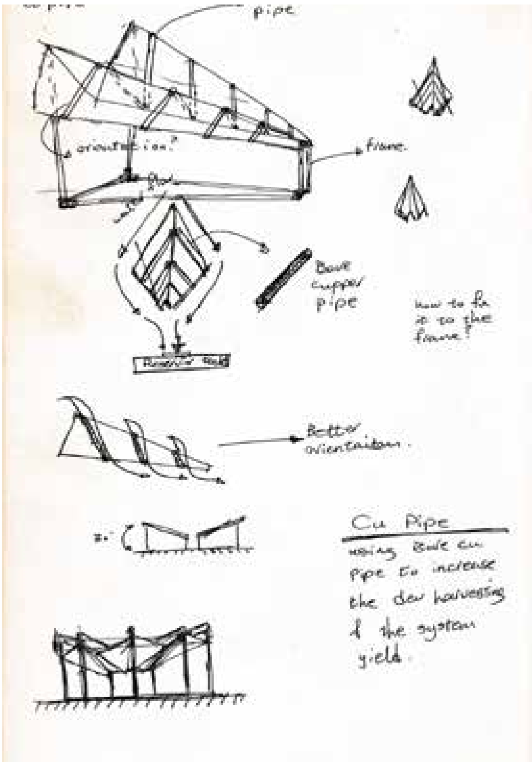
All of this leads the author to look for other sources of inspiration beside the scientific ground and database, this of course, does not mean to neglect or ignore the scientific findings but to find alternative information sources. The best sources for such purposes was nature, by looking at the plants and insects and how they evolved to adapt to drought was fascinating. This gave a much wider perspective and more freedom in designing a new concepts based on both literature and nature findings.

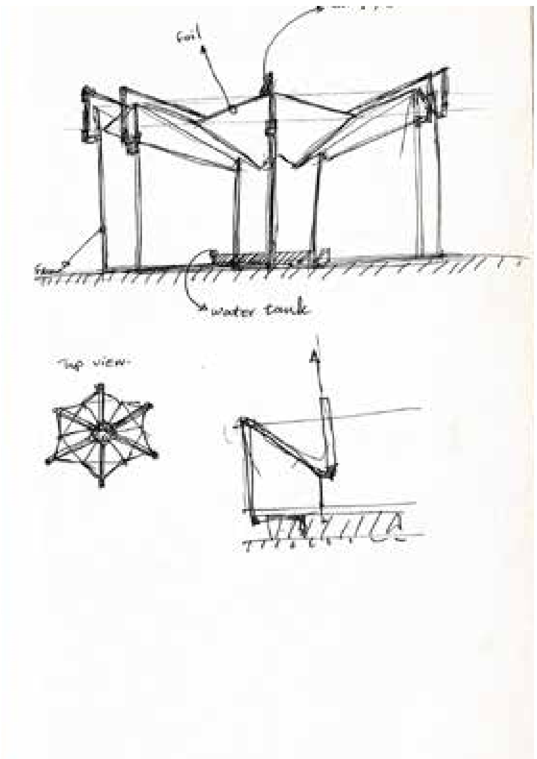
05. Appendices

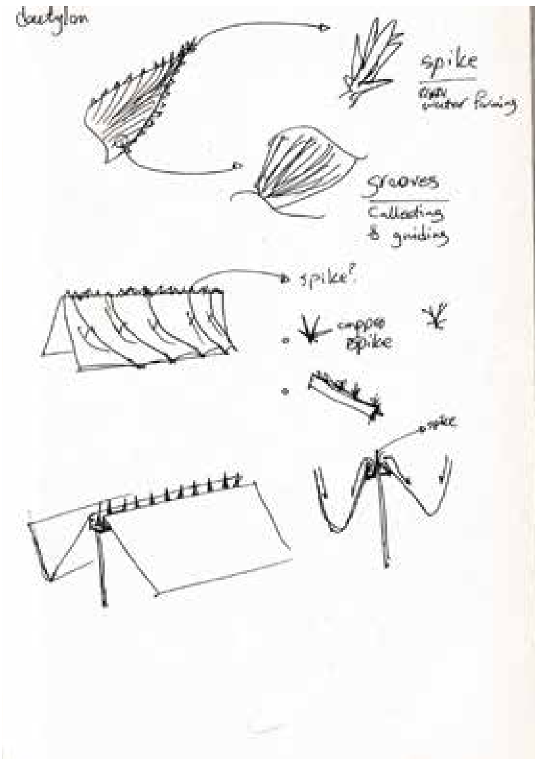
Appendices

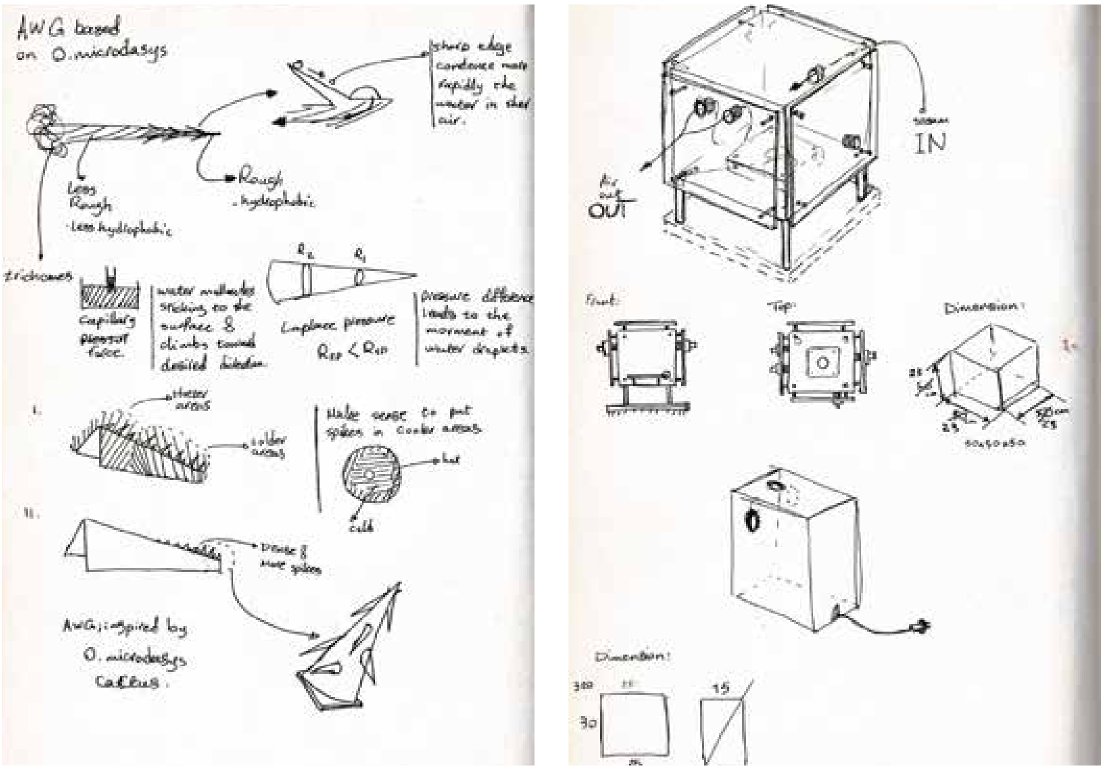
Appendix 01











Appendix 01. Sketches and concepting process of designing the Dew collector copper line

06. References

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